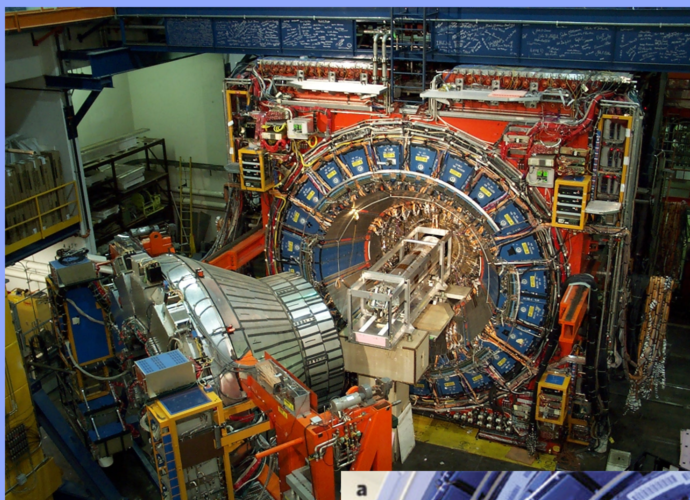
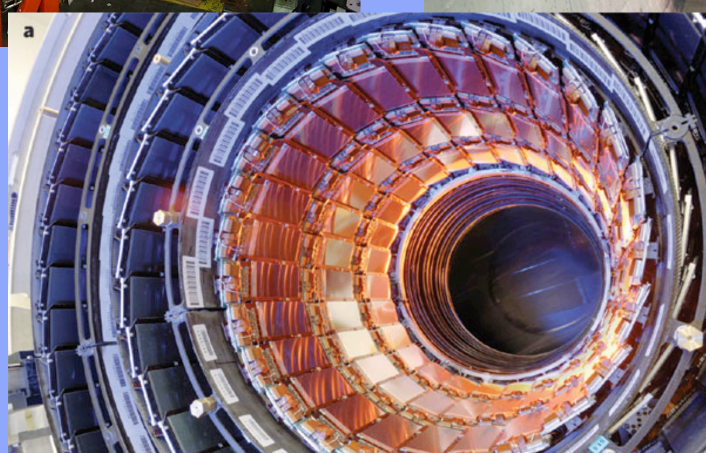
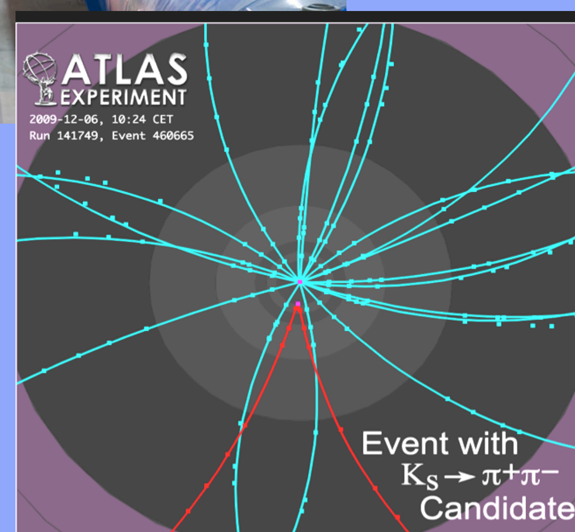
Particle Physics from Tevatron to LHC: what we know and what we hope to discover







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Università di Pisa, February 2010

Outline

- **Introduction**
  - Outstanding problems in particle physics
    - and the role of hadron colliders
  - Current and near future colliders: Tevatron and LHC
- **Standard Model Measurements**
  - Hadron-hadron collisions
  - Cross Section Measurements of jets, W/Z bosons and top quarks
- **Constraints on and Searches for the Higgs Boson**
  - W boson and Top quark mass measurements
  - Standard Model Higgs Boson
- **Searches for New Physics**
  - Supersymmetry
  - Higgs Bosons beyond the Standard Model
  - High Mass Resonances (Extra Dimensions etc.)
- **First Results from the 2009 LHC run**

Hadron-Hadron Collisions

Calculating a Cross Section

- Cross section is convolution of pdf's and Matrix Element

Physical cross section

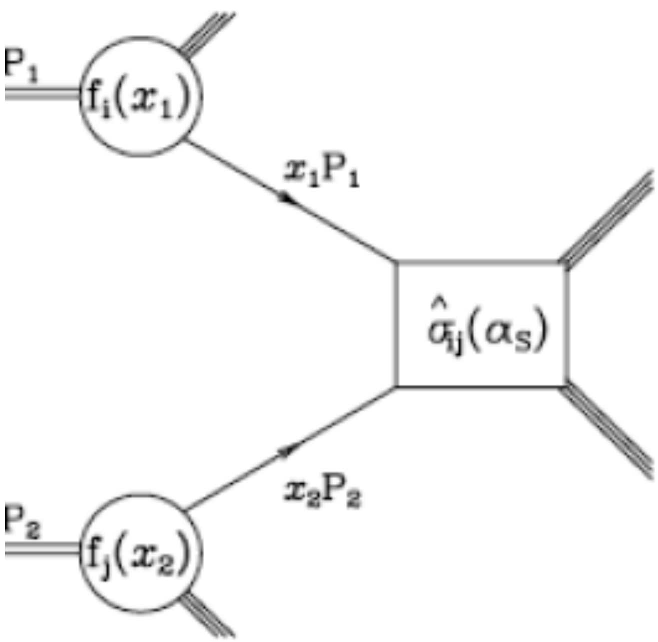
Parton distribution function

Renormalization scale μ_R

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2\, f_i(x_1, \mu_F) f_j(x_2, \mu_F)\, \hat{\sigma}_{ij}(p_1, p_2, \alpha_S(\mu_R), Q^2, \mu_R, \mu_F).$$

Factorization scale μ_F

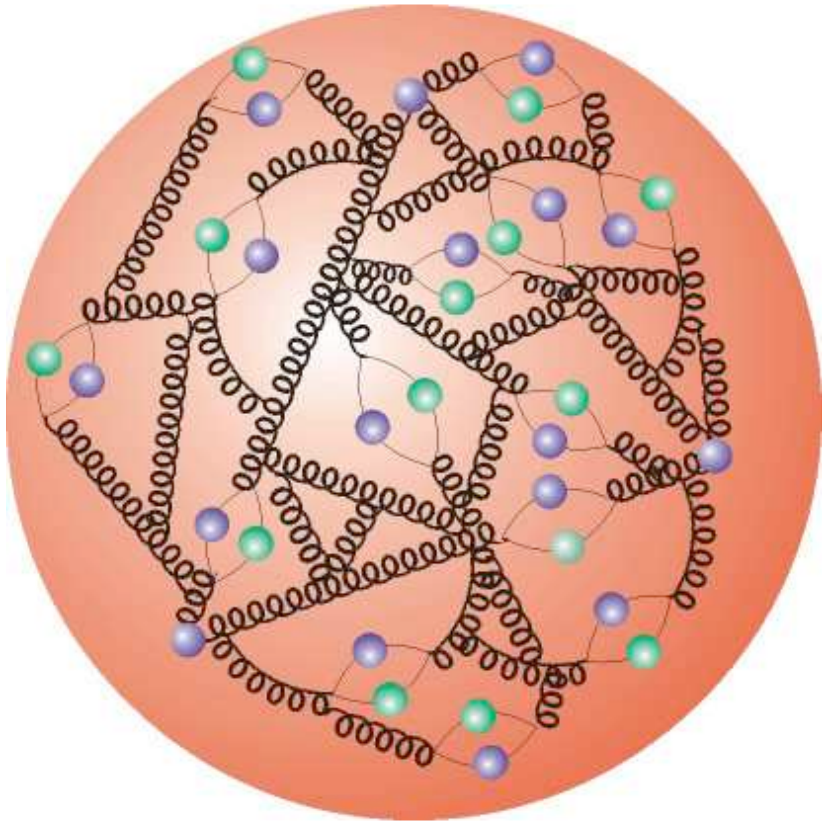
Short distance cross section, calculated as a perturbation series in α_S



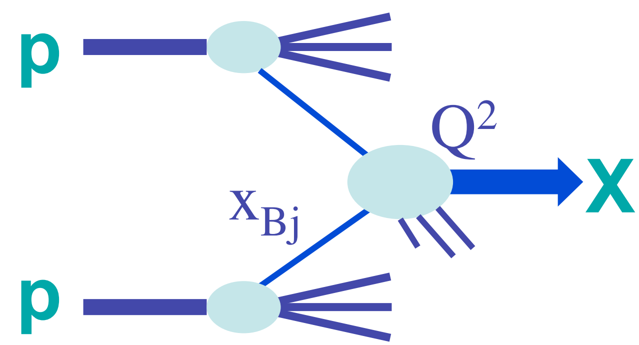
- Calculations are done in perturbative QCD
  - Possible due to factorization of hard ME and pdf's
    - Can be treated independently
  - Strong coupling (α_s) is large
    - Higher orders needed
    - Calculations complicated

The Proton Composition

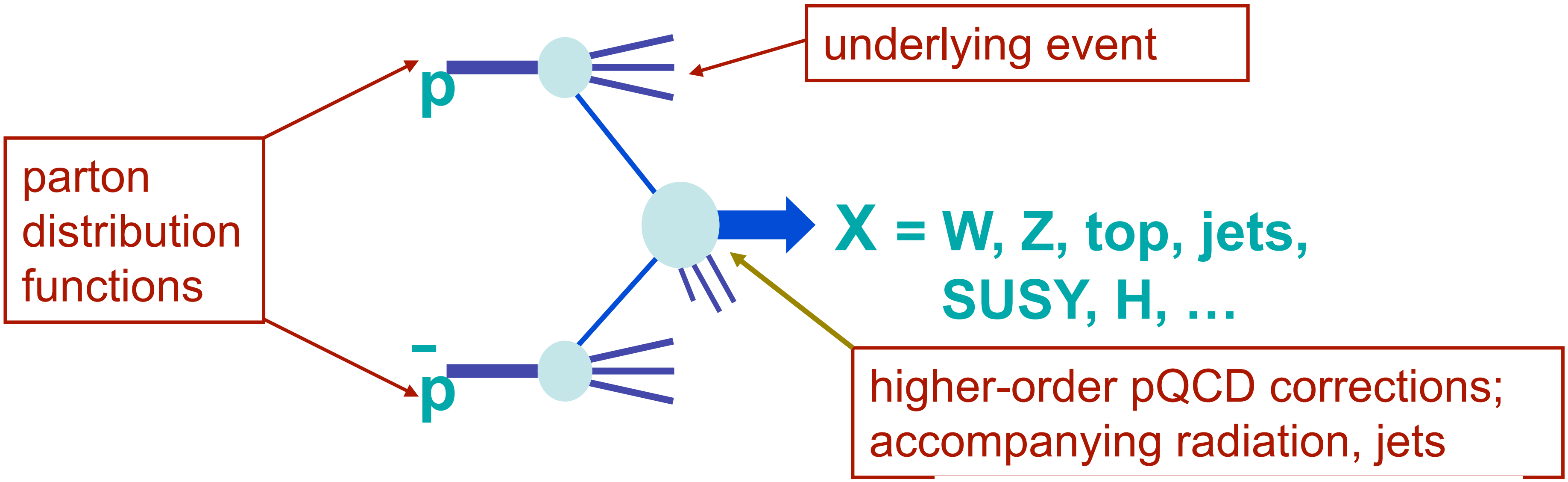
- It's complicated:
  - Valence quarks, Gluons, Sea quarks
- Exact mixture depends on:
  - Q^2: ~$(M^2+p_T^2)$
  - Björken-x:
    - fraction or proton momentum carried by parton
- Energy of parton collision:



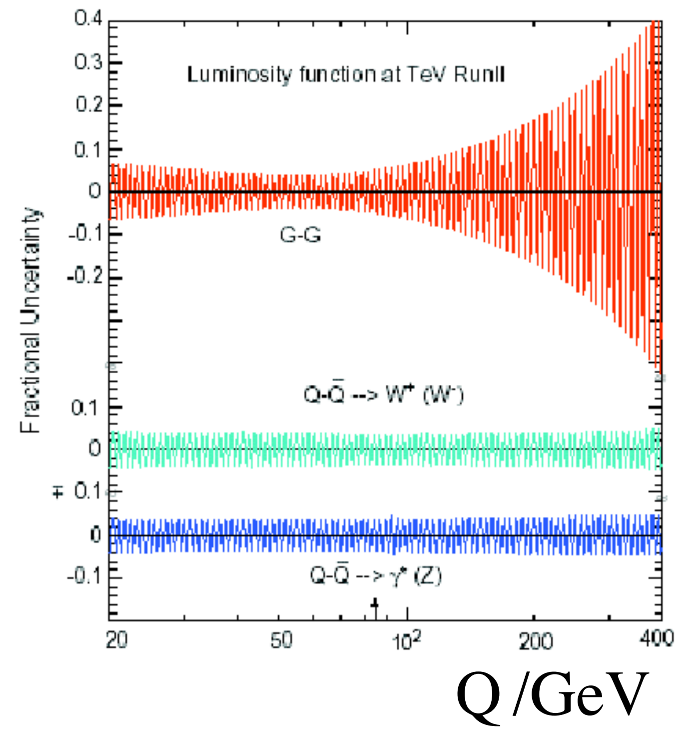
$$\boxed{\hat{s} = x_p \cdot x_{\bar{p}} \cdot s \qquad M_X = \sqrt{\hat{s}}}$$



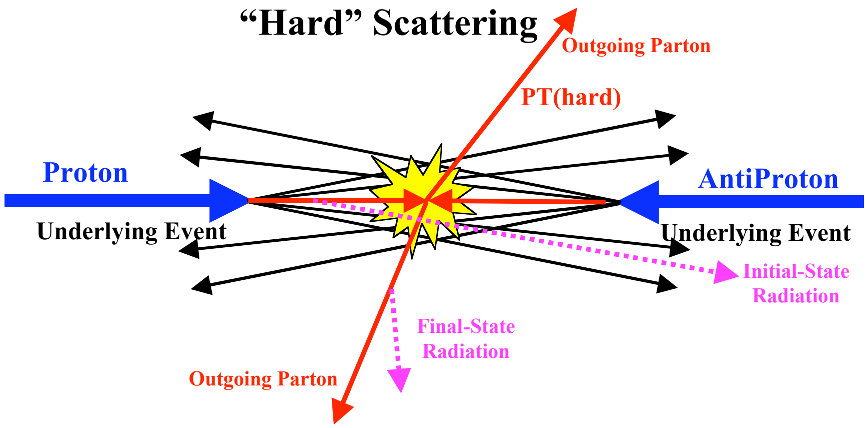
The Proton is Messy



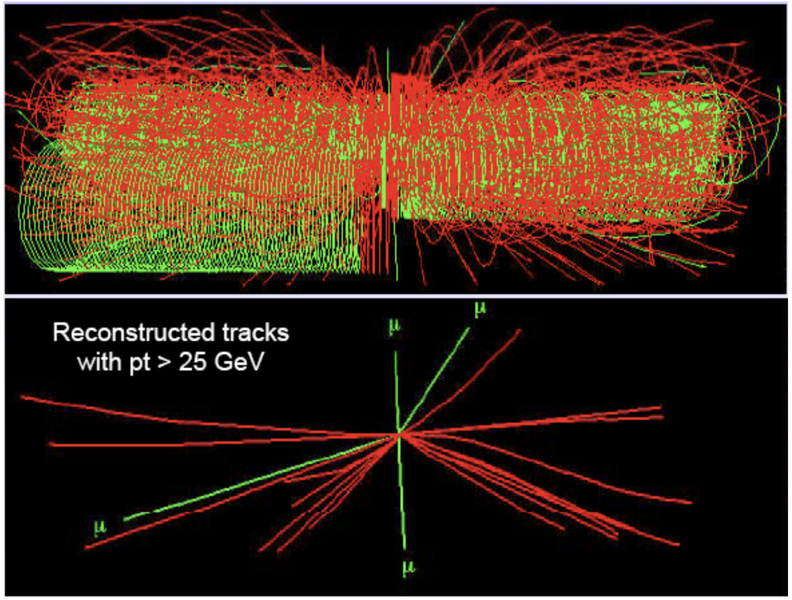
- We don't know
  - Which partons hit each other
  - What their momentum is
  - What the other partons do
- We know roughly (2-30%)
  - The parton content of the proton
  - The cross sections of processes



Every Event is Complicated

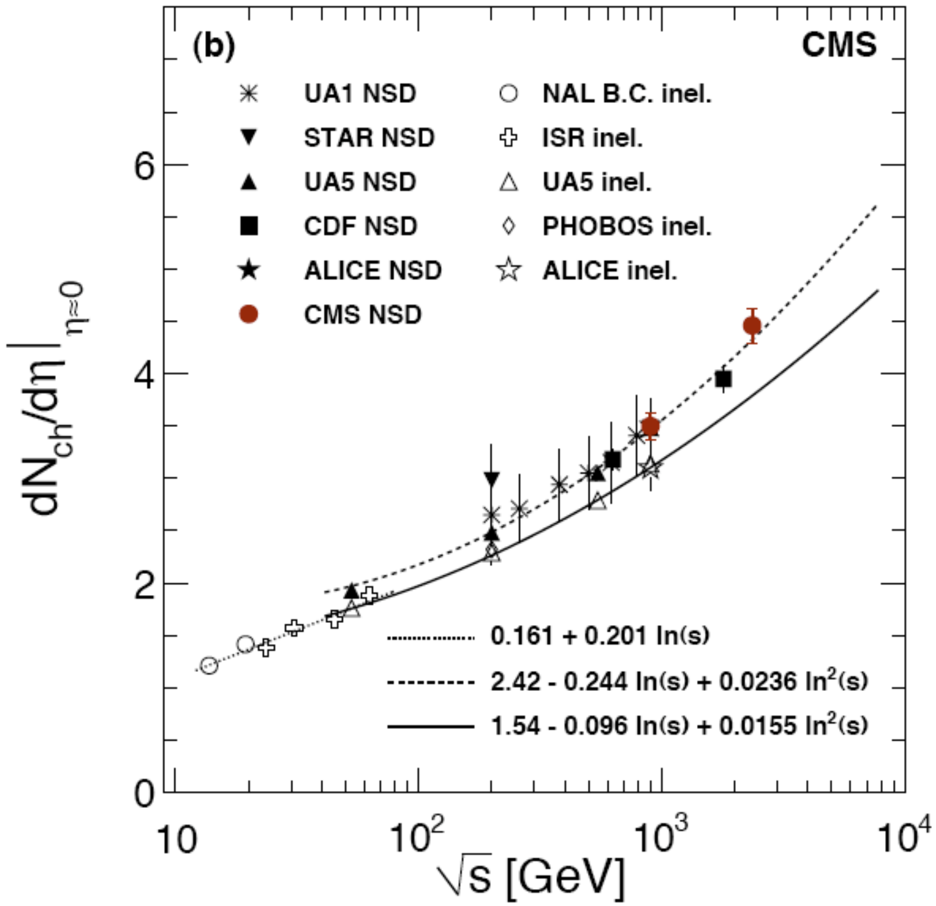


$H \rightarrow ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-)$



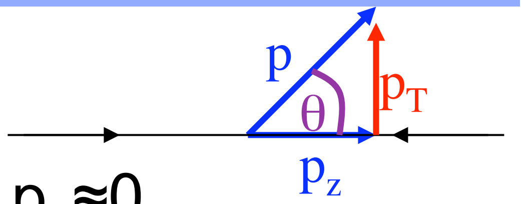
- "Underlying event":
  - Initial state radiation
  - Interactions of other partons in proton
- Additional pp interactions
  - On average 20 at design luminosity of LHC
- Many forward particles escape detection
  - Transverse momentum ~0
  - Longitudinal momentum >>0

Number of Particles per Event



- First measurements of ALICE and CMS
  - Number of particles per unit η:
    - 3.5 at 0.9 TeV and 4.5 at 2.36 TeV => ≈ 6 at 7 TeV?

Kinematic Constraints and Variables



- **Transverse momentum, p_T**
  - Particles that escape detection ($\theta<3^o$) have $p_T \approx 0$
  - Visible transverse momentum conserved $\sum_i p_T^i \approx 0$
    - **Very useful variable!**
- **Longitudinal momentum and energy, p_z and E**
  - Particles that escape detection have large p_z
  - Visible p_z is not conserved
    - **Not a useful variable**
- **Polar angle θ**
  - Polar angle θ is not Lorentz invariant
  - Rapidity: y
  - Pseudorapidity: η

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

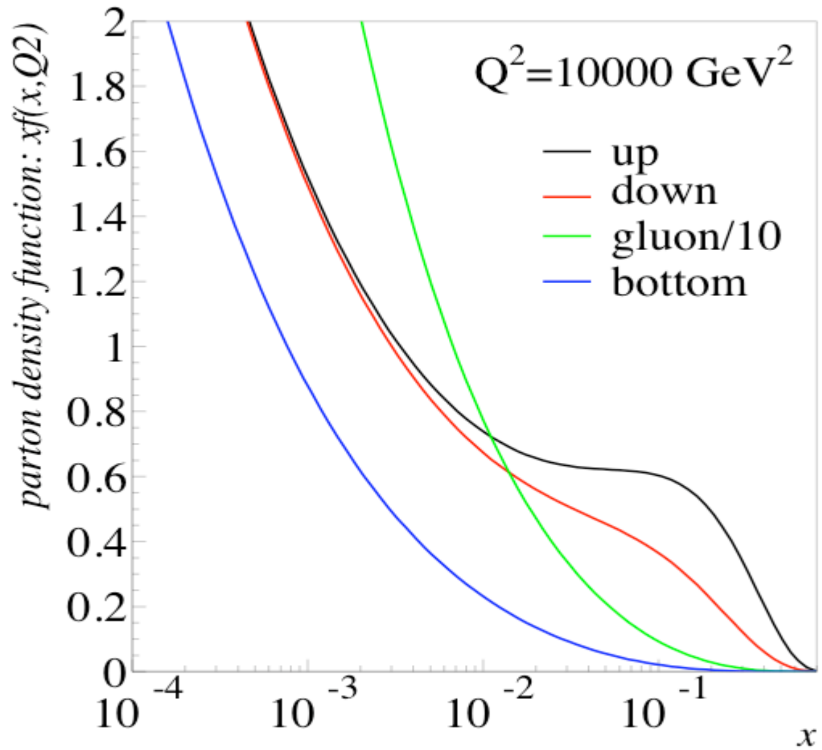
For M=0

$$y = \eta = -\ln(\tan\frac{\theta}{2})$$

Parton Kinematics

- Examples:
  - Higgs: M~100 GeV/c^2
    - LHC: $\langle x_p \rangle$=100/14000≈0.007
    - TeV: $\langle x_p \rangle$=100/2000≈0.05
  - Gluino: M~1000 GeV/c^2
    - LHC: $\langle x_p \rangle$=1000/14000≈0.07
    - TeV: $\langle x_p \rangle$=1000/2000≈0.5

pdf's measured in deep-inelastic scattering

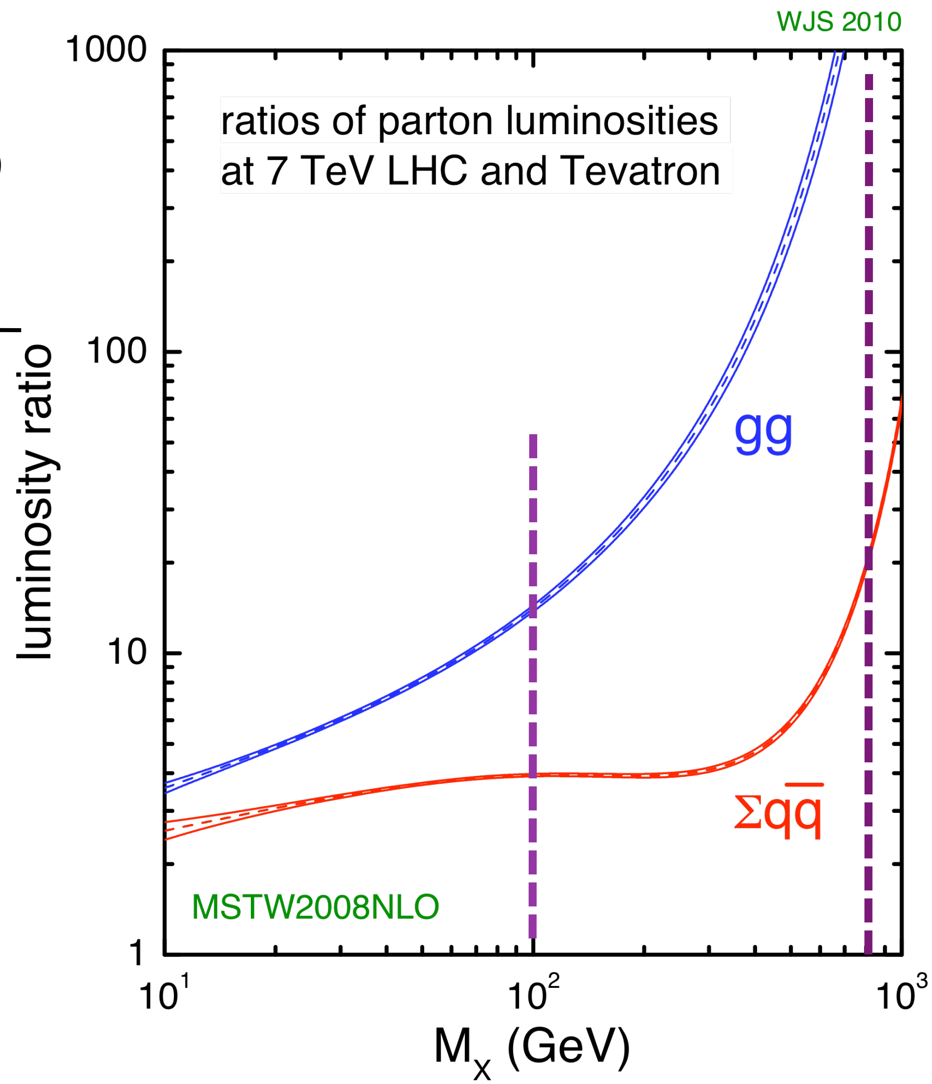


- Parton densities rise dramatically towards low x
  - Results in larger cross sections for LHC, e.g.
    - factor ~1000 for gluinos
    - factor ~40 for Higgs
    - factor ~10 for W's

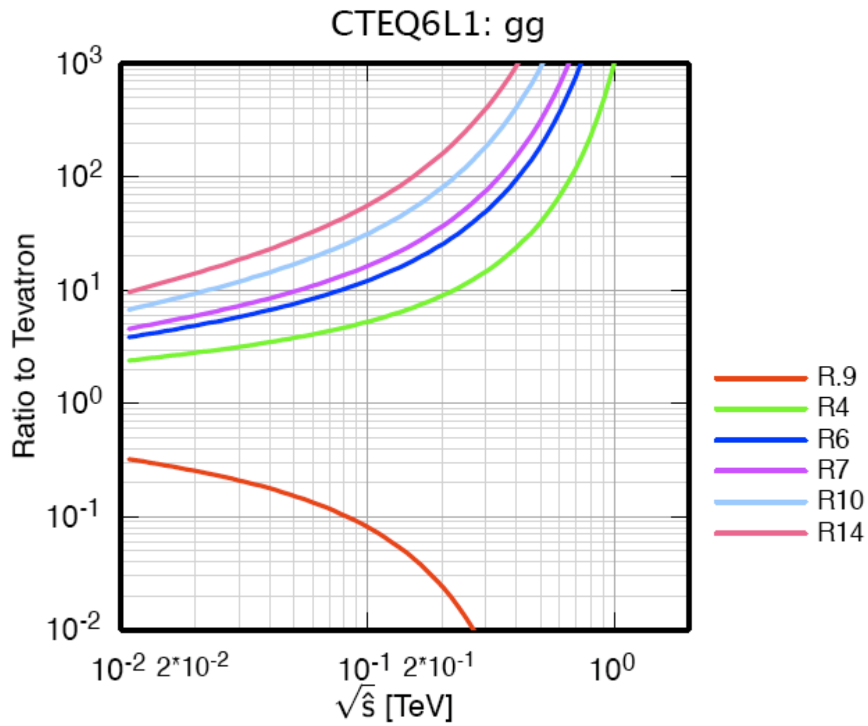
(at $\sqrt{s}$=14 TeV)

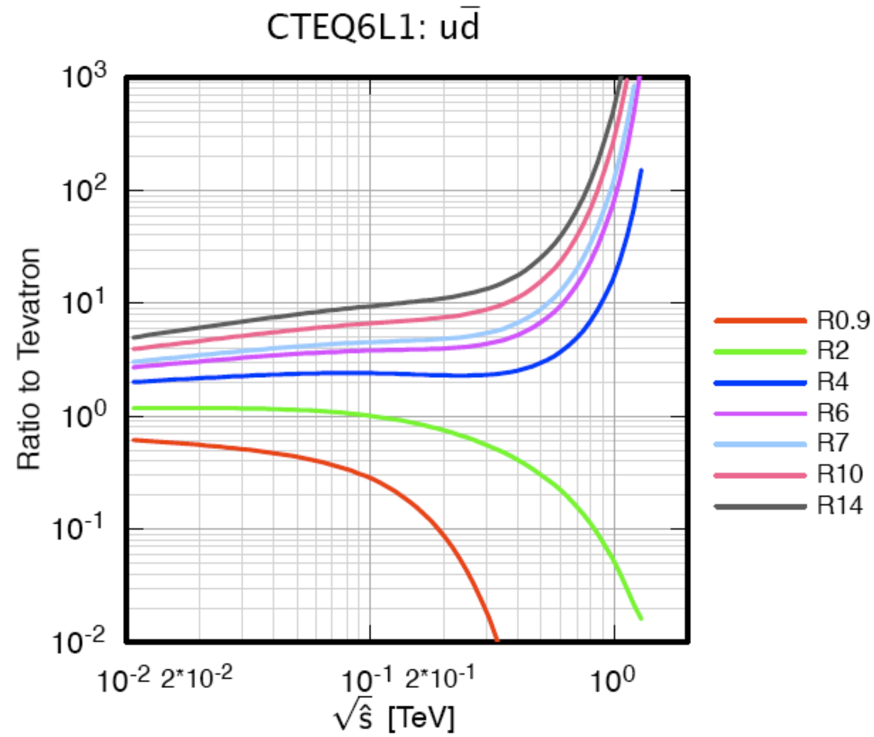
Ratio of Luminosity: LHC at 7 TeV vs Tevatron

- Power of collider can be fully characterized by ratio of parton luminosities
- Ratio larger for gg than $q\bar{q}$
  - Due to steep rise of gluon towards low x
- M_X=100 GeV
  - gg: R≈10, e.g. Higgs
  - $q\bar{q}$: R≈3, e.g. W and Z
- M_X=800 GeV
  - gg: R≈1000, e.g. SUSY
  - $q\bar{q}$: R≈20, e.g. Z'



More on Parton Luminosities





- Looking at these in detail gives excellent idea about relative power of LHC vs Tevatron, i.e.
  - How much luminosity is needed for process X at LHC to supersede the Tevatron?
  - And how much is gained later when going to 14 TeV
- Plots from C. Quigg: *LHC Physics Potential versus Energy*, arXiv: 0908.3660

Standard Model Cross Section Measurements as test of QCD

- Jets
- W and Z bosons
- Top Quark Production

What is a Cross Section?

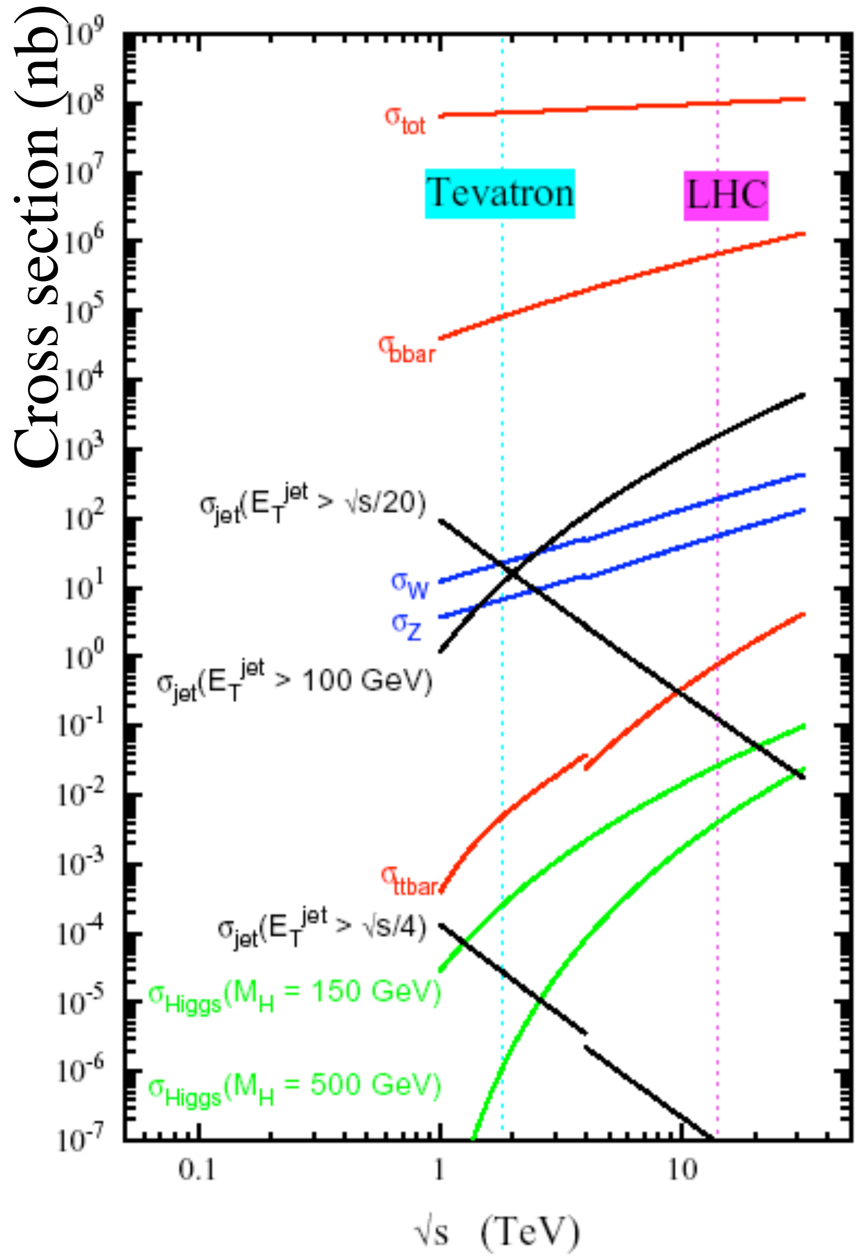
- Differential cross section: $d\sigma/d\Omega$:
  - Probability of a scattered particle in a given quantum state per solid angle $d\Omega$
    - E.g. Rutherford scattering experiment
- Other differential cross sections: $d\sigma/dE_T$(jet)
  - Probability of a jet with given E_T
- Integrated cross section
  - Integral: $\sigma = \int d\sigma/d\Omega \, d\Omega$

Measurement: $\boxed{\sigma=(N_{obs}-N_{bg})/(\varepsilon L)}$

Luminosity

Cross Sections at LHC

- A lot more "uninteresting" than "interesting" processes at design luminosity ($L=10^{34}$ $cm^{-2}s^{-1}$)
  - Any event: 10^9 / second
  - W boson: 150 / second
  - Top quark: 8 / second
  - Higgs (150 GeV): 0.2 / second
- **Trigger** filters out interesting processes
  - Makes fast decision of whether to keep an event at all for analysis
  - Crucial at hadron colliders
- Dramatic increase of some cross sections from Tevatron to LHC
  - Improved discovery potential at LHC



Luminosity Measurement

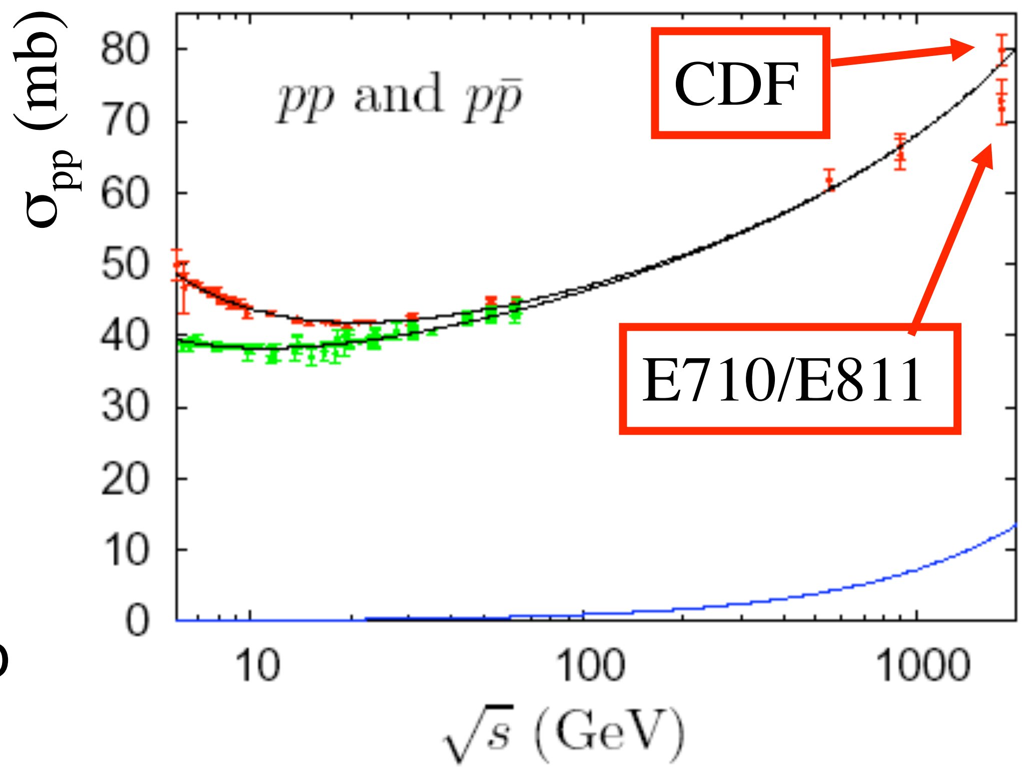
$$R_{pp} = \mu_{pp} \cdot f_{BC} = \sigma_{inel} \cdot \varepsilon_{pp} \cdot \delta(L) \cdot L$$

σ_{LM}

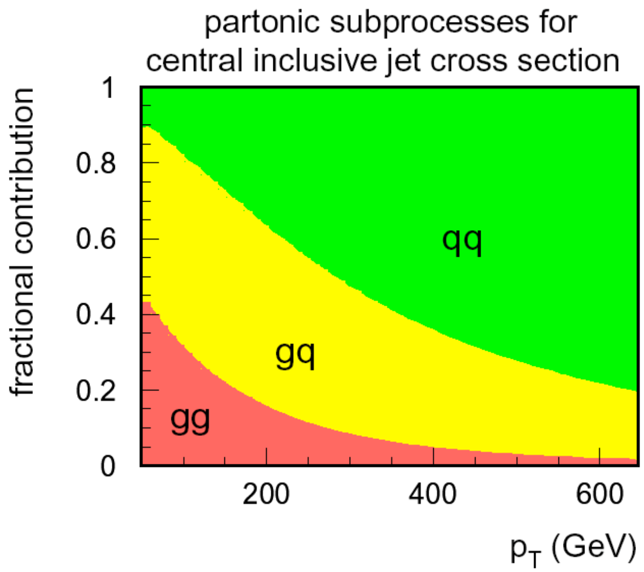
L – luminosity
f_{bc} – Bunch Crossing rate
μ_a – # of pp / BC

σ_{inel} – inelastic x-section
ε_{pp} – acceptance for a single pp
$\delta(L)$ – detector non-linearity

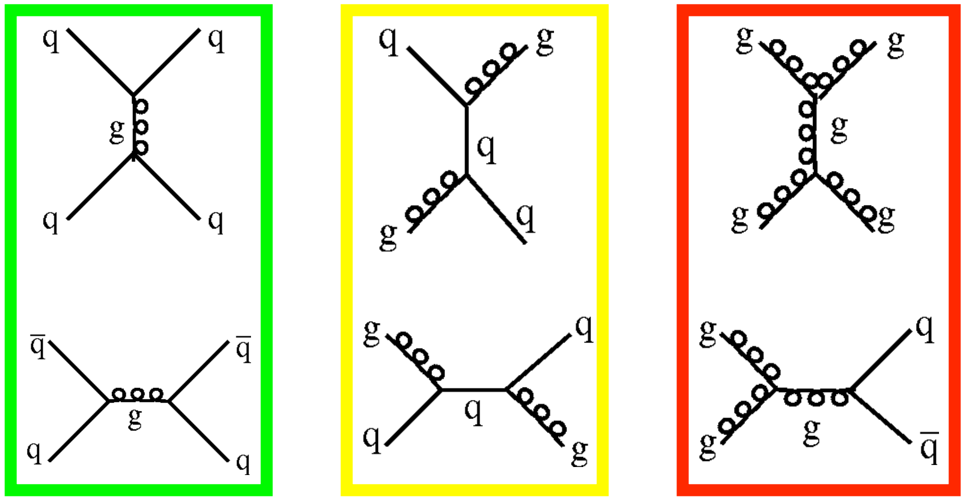
- Measure events with 0 interactions
  - Related to R_{pp}
- Normalize to measured inelastic pp cross section
  - Tevatron: 60.7+/-2.4 mb
  - LHC: 70-120 mb ?

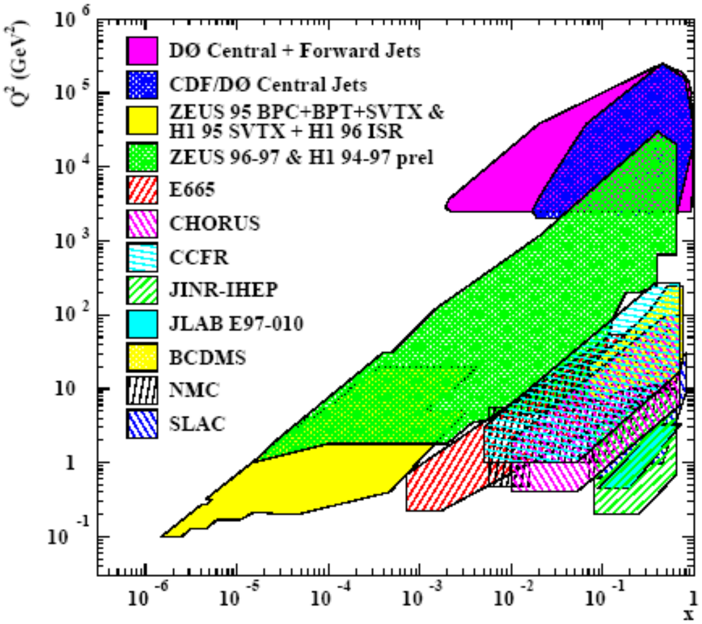


Jet Cross Sections



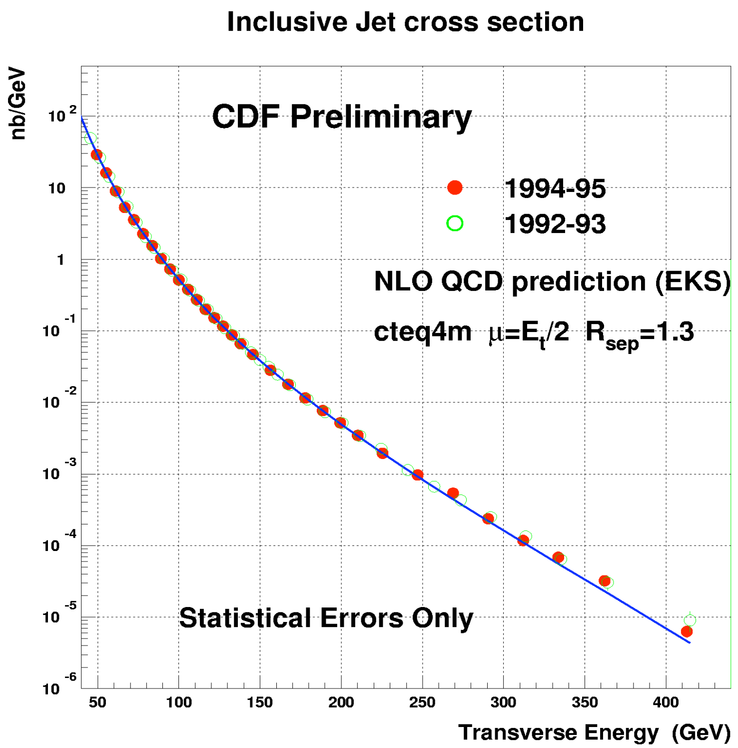
- Inclusive jets: processes qq, qg, gg

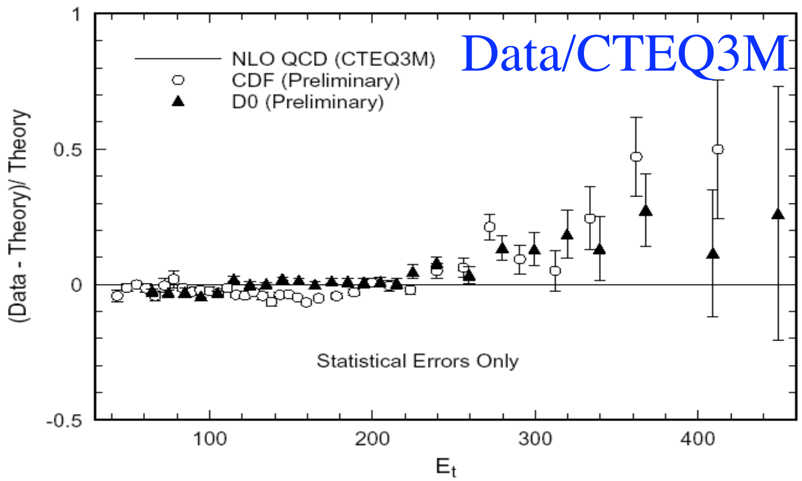




- Highest E_T probes shortest distances
  - Tevatron: $r_q<10^{-18}$ m
  - LHC: $r_q<10^{-19}$ m (?)
  - Could e.g. reveal substructure of quarks
- Tests perturbative QCD at highest energies

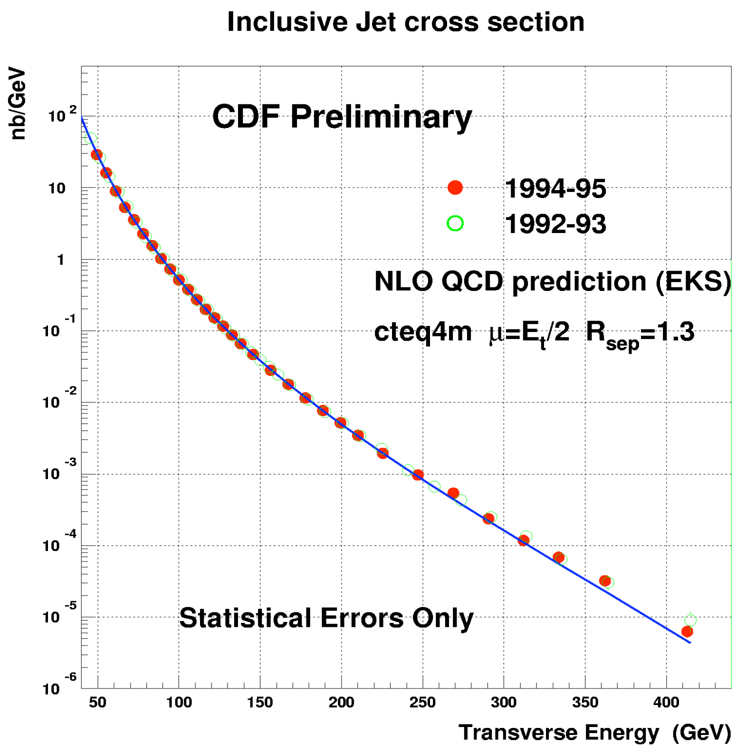
Jet Cross Section History



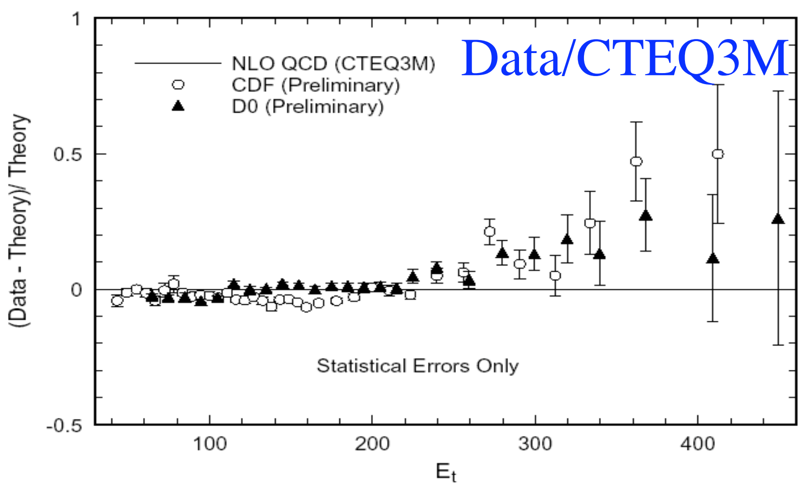


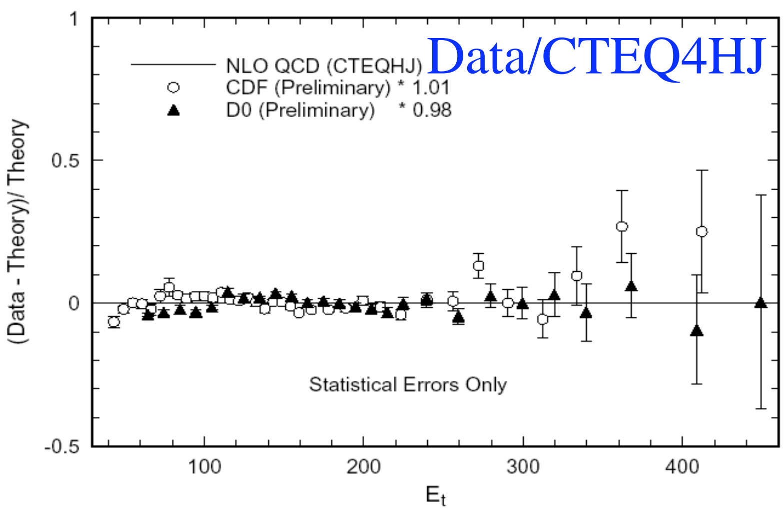
- Run I (1996):
  - Excess at high E_T
  - Could be signal for quark substructure?!?

Jet Cross Section History

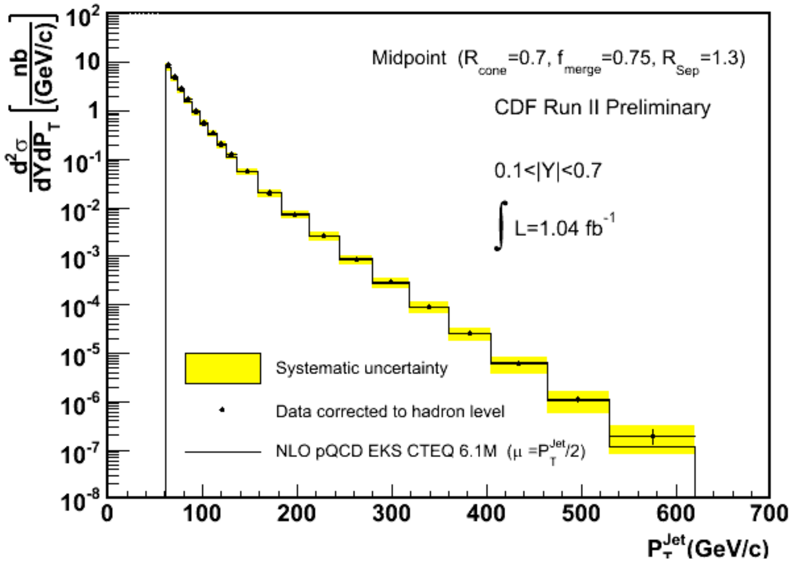


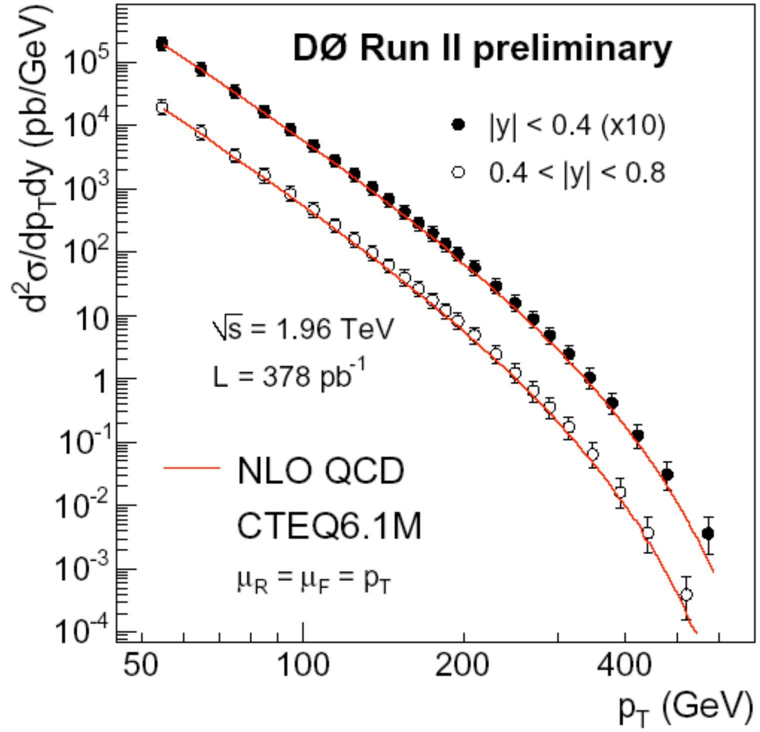
- Since Run I:
  - Revision of parton density functions
    - Gluon is uncertain at high x
    - It including these data describes data well

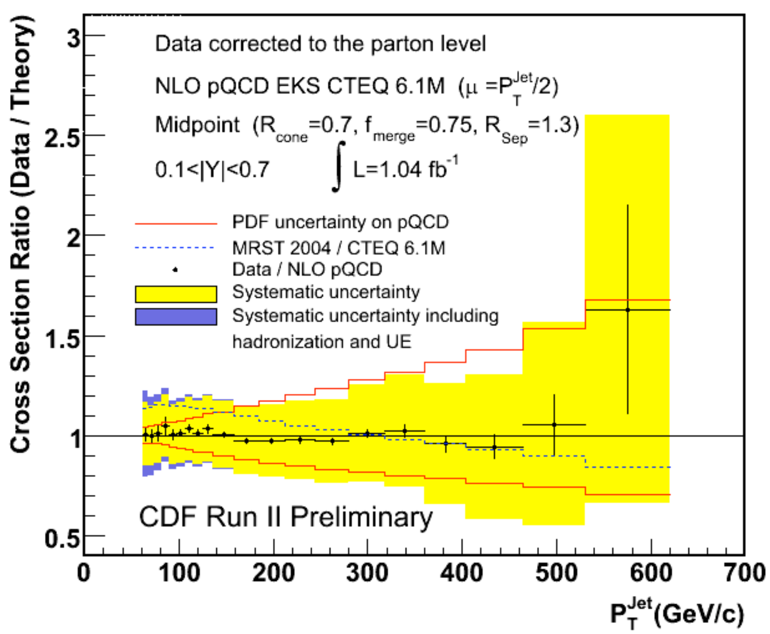




Jet Cross Sections in Run II

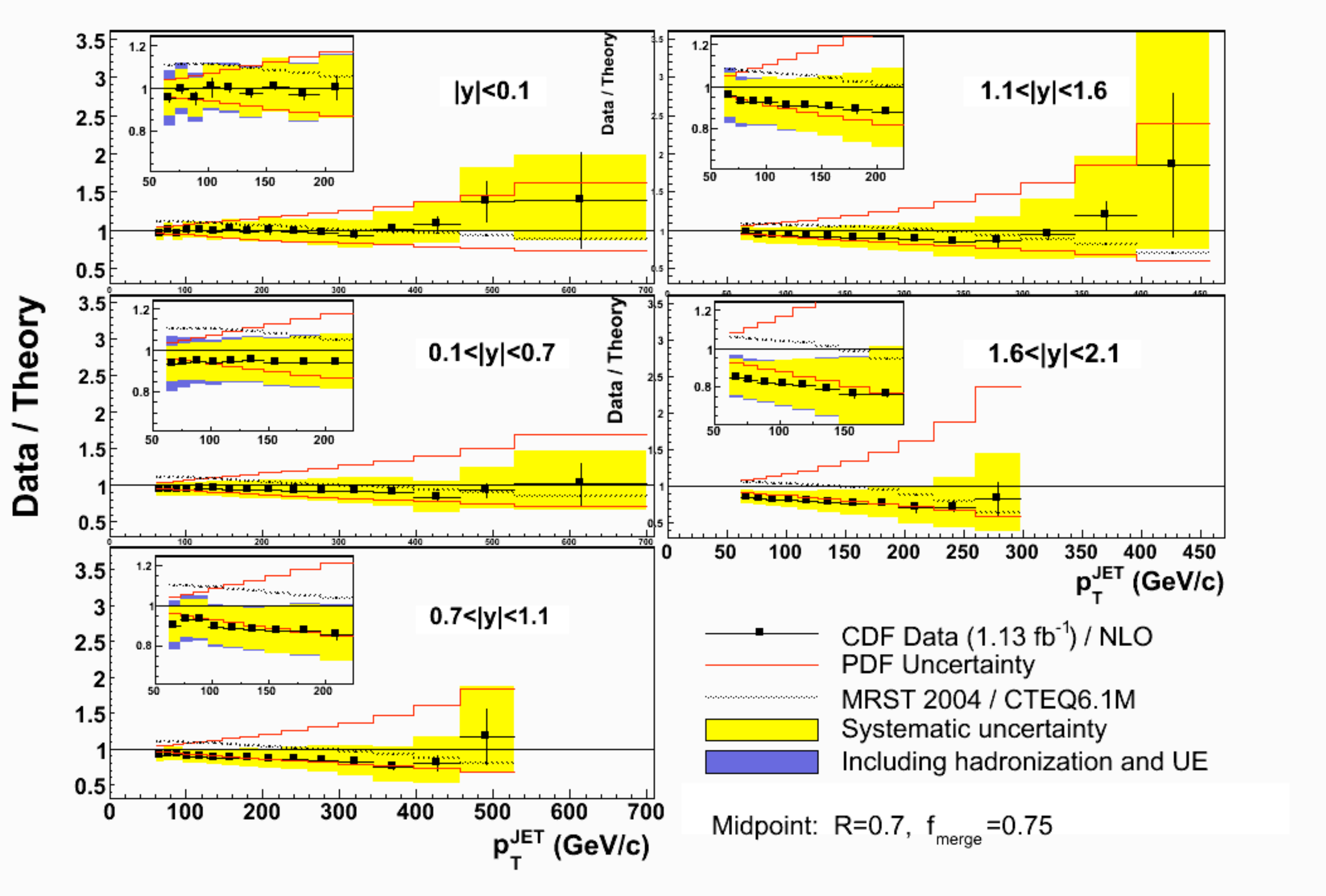






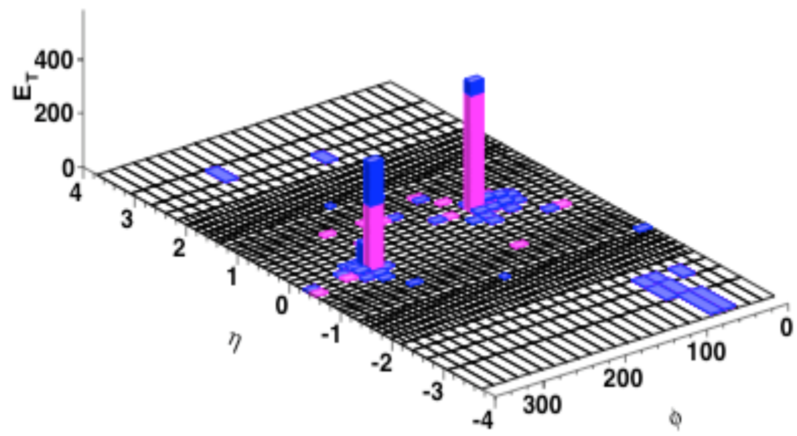
- Excellent agreement with QCD calculation over 8 orders of magnitude!
- No excess any more at high E_T
  - Large pdf uncertainties will be constrained by these data

New Physics or PDF's?



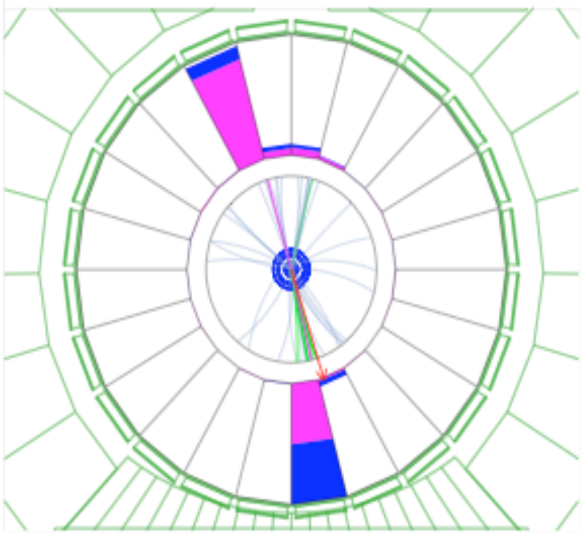
- Measure in different rapidity bins:
  - New physics: high p_T and central y (⇔ high Q^2)
  - PDF's: high y (⇔ high x)

High Mass Dijet Event: M=1.4 TeV



CDF Run II Preliminary

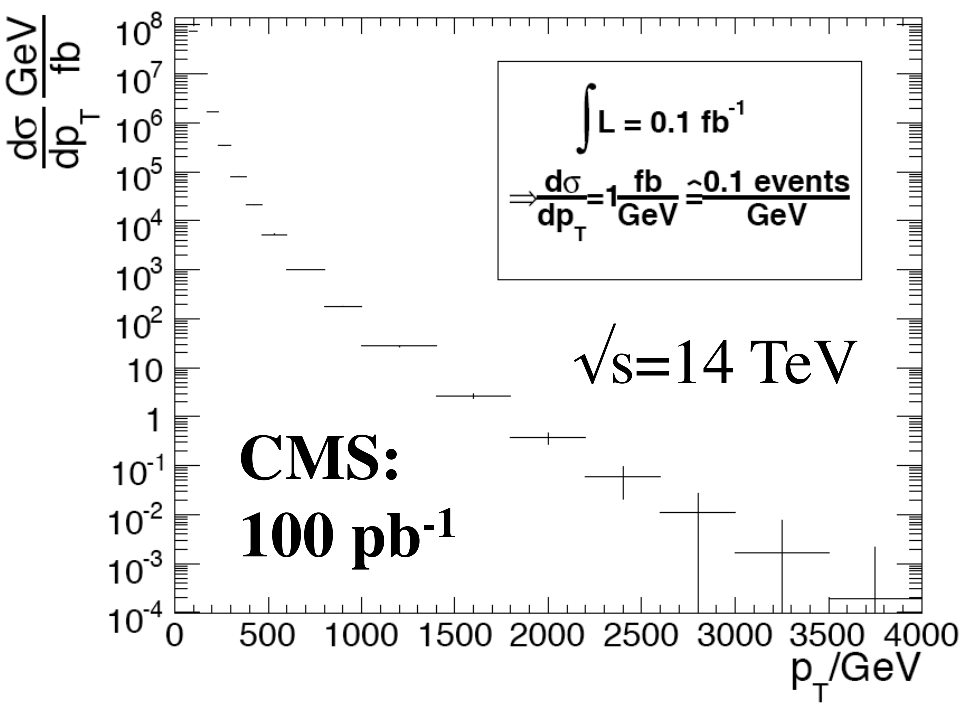
```
Jet Et1 = 666 GeV (corr)
          583 GeV (raw)
eta1    = 0.31 (detector)
          0.43 (corr z)

Jet Et2 = 633 GeV (corr)
          546 GeV (raw)
eta2    = -0.30 (detector)
          -0.19 (corr z)
```



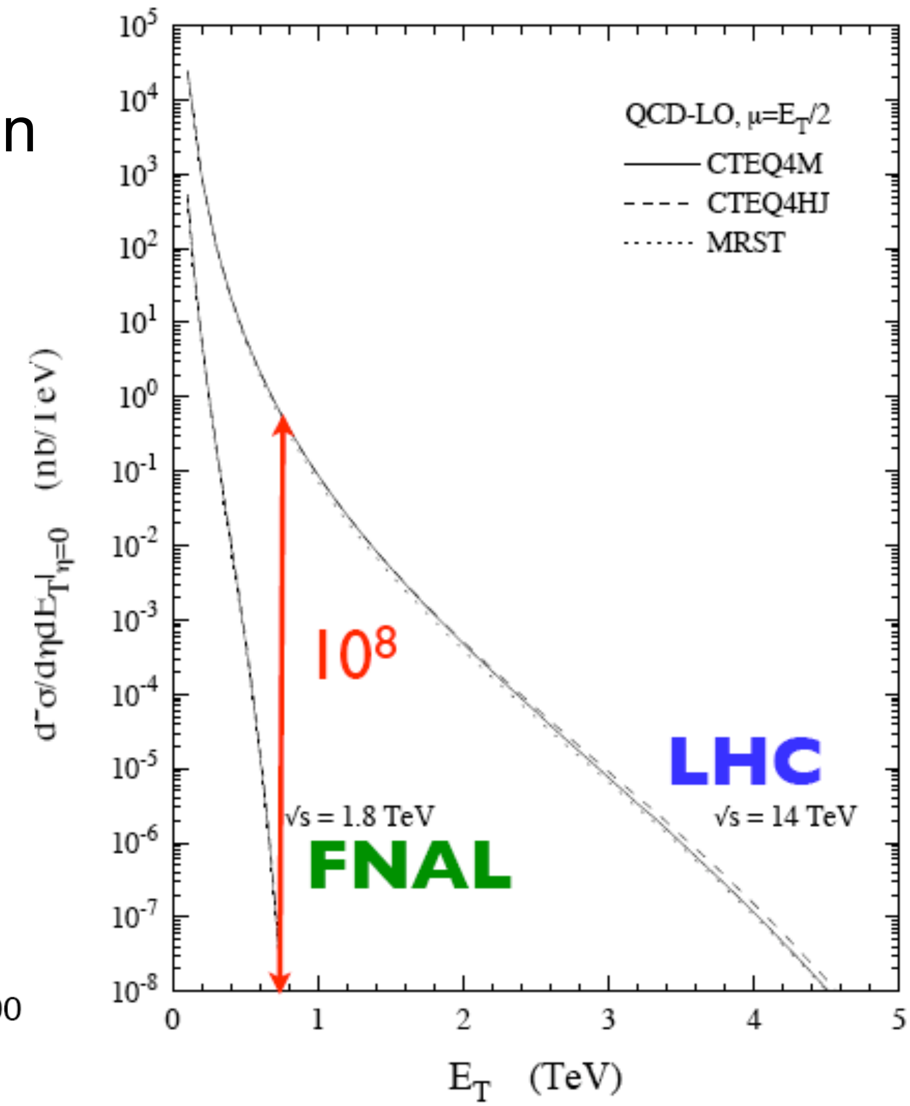
```
Run    152507
Event  1222318

DiJet Mass = 1364 GeV (corr)

z vertex    = -25 cm
```

Jets at the LHC

- Much higher rates than at the Tevatron
  - Gluon dominated production
  - At 500 GeV: ~1000 times more jets ($\sqrt{s}$ = 7 TeV)

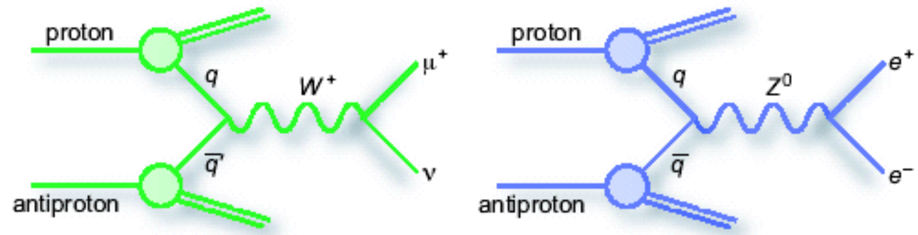


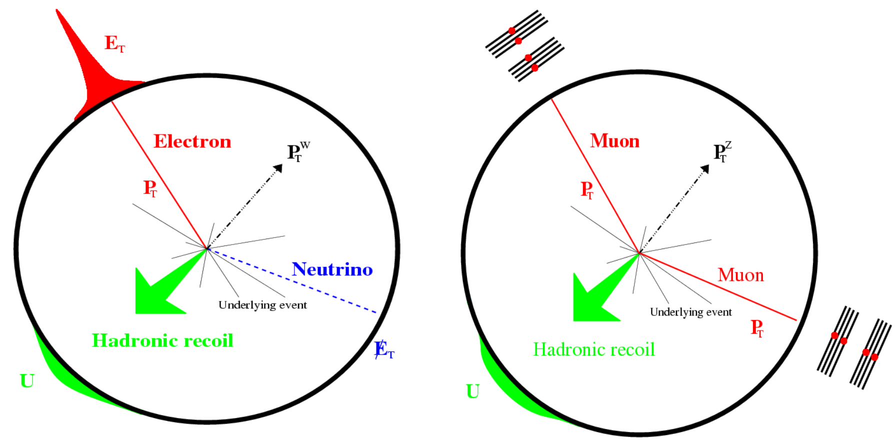
Jet Cross Section



W and Z Bosons

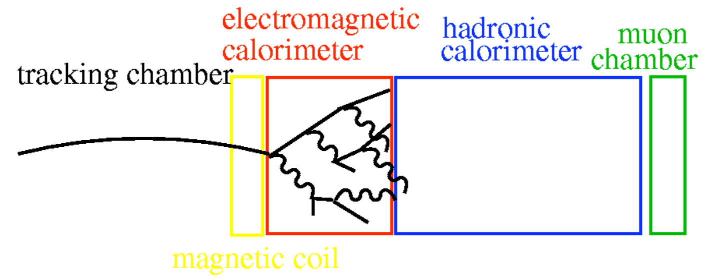
- Focus on leptonic decays:
  - Hadronic decays ~impossible due to enormous QCD dijet background
- Selection:
  - Z:
    - Two leptons p_T>20 GeV
      - Electron, muon, tau
  - W:
    - One lepton p_T>20 GeV
    - Large imbalance in transverse momentum
      - Missing E_T>20 GeV
      - Signature of undetected particle (neutrino)
- Excellent calibration signal for many purposes:
  - Electron energy scale
  - Track momentum scale
  - Lepton ID and trigger efficiencies
  - Missing E_T resolution
  - Luminosity …



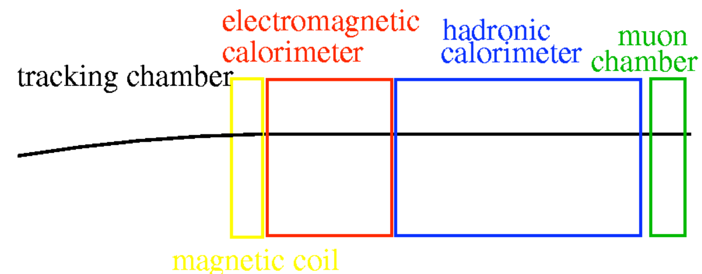


Lepton Identification

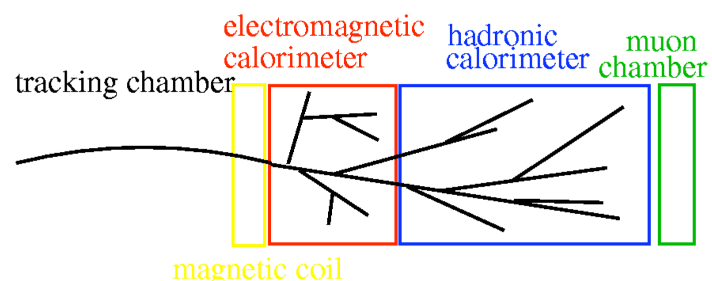
- Electrons:
  - compact electromagnetic cluster in calorimeter
  - Matched to track



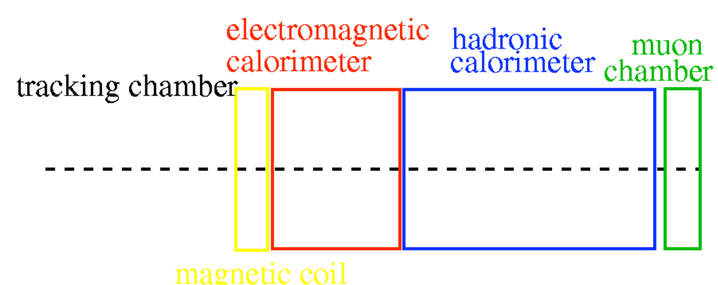
- Muons:
  - Track in the muon chambers
  - Matched to track



- Taus:
  - Narrow jet
  - Matched to one or three tracks

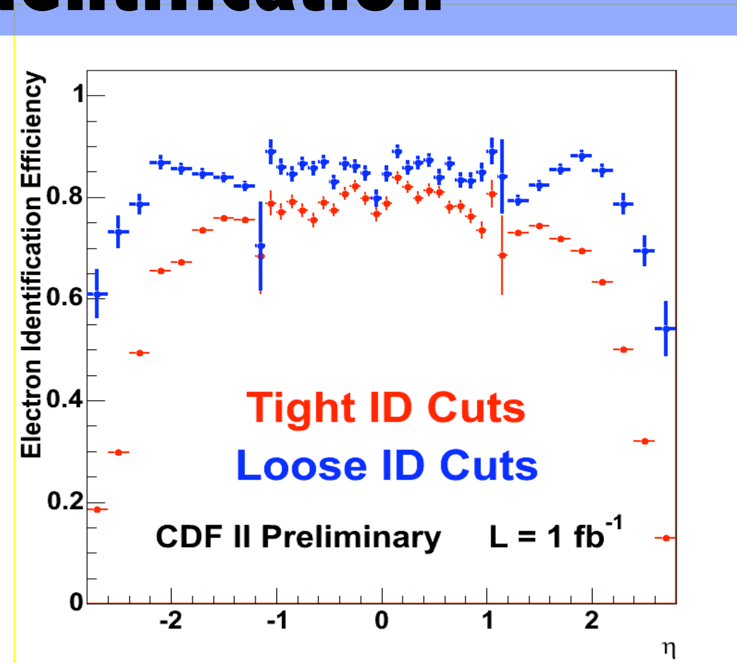


- Neutrinos:
  - Imbalance in transverse momentum
  - Inferred from total transverse energy measured in detector
  - More on this in Lecture 4

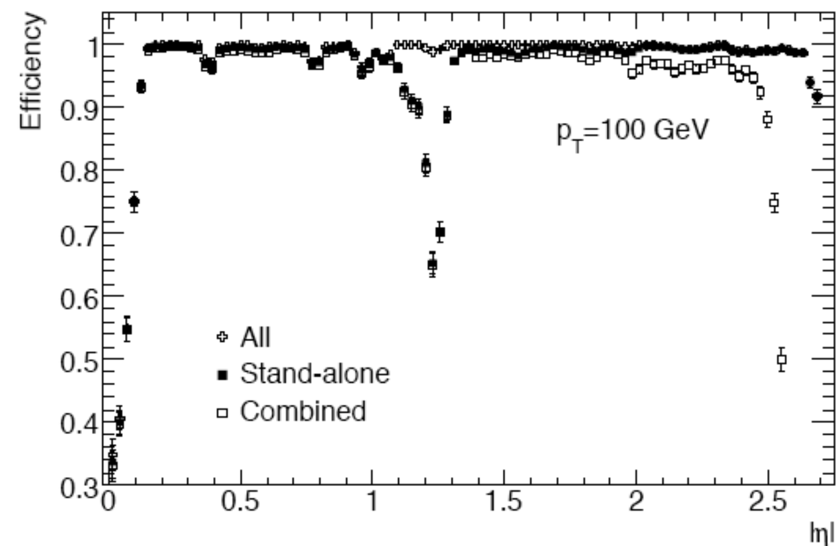


Electron and Muon Identification

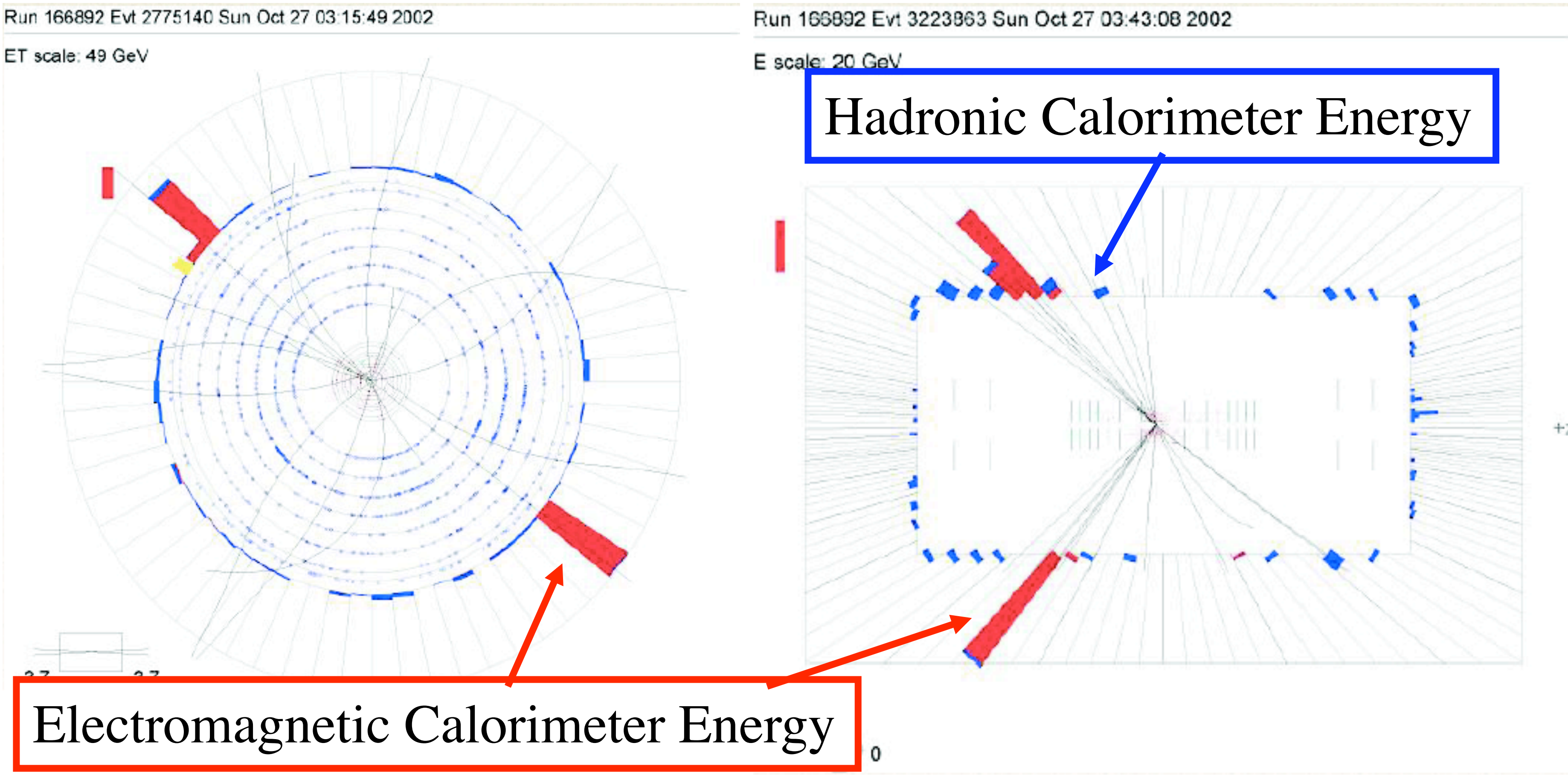
- Desire:
  - High efficiency for isolated electrons
  - Low misidentification of jets



- Performance:
  - Efficiency:
    - 60-100% depending on |η|
    - Measured using Z's



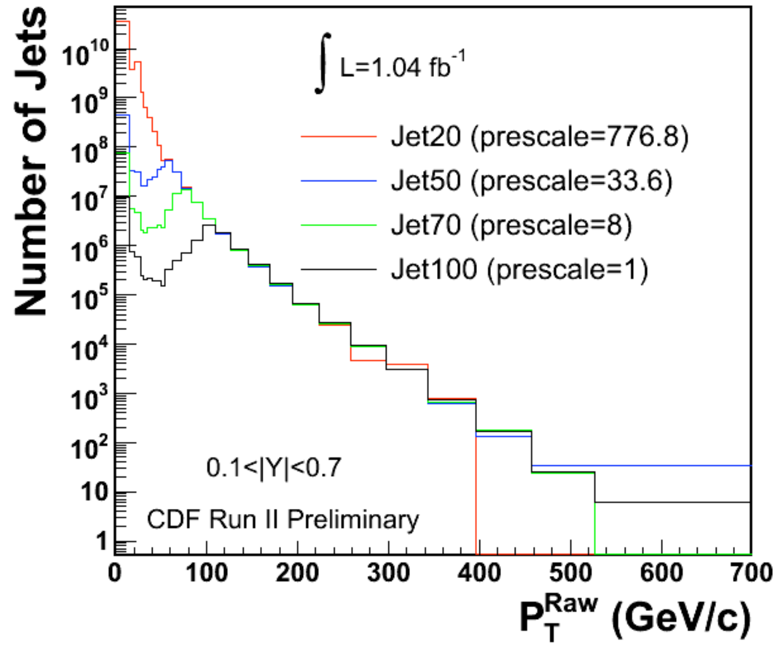
Electrons and Jets



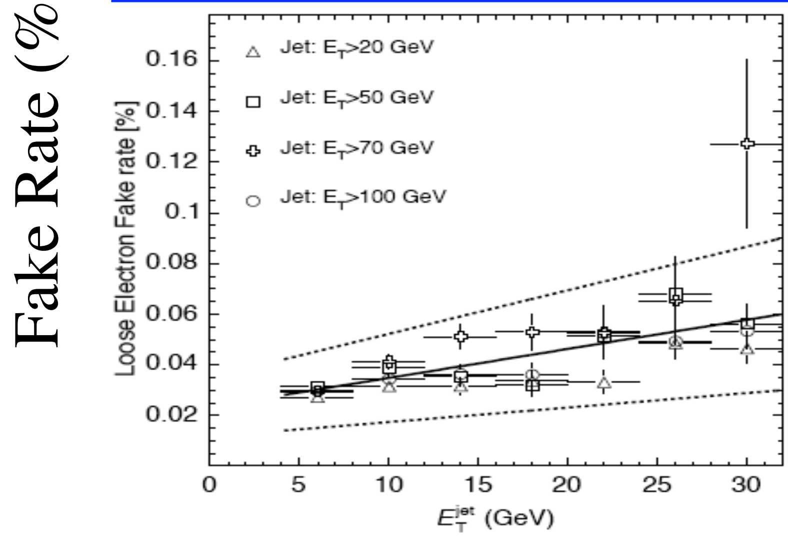
- Jets can look like electrons, e.g.:
  - photon conversions from π^0's:
    - ~30% of photons convert in ATLAS (13% in CDF)
  - early showering charged pions
- And there are lots of jets!!!

Jets faking Electrons

- Jets can pass electron ID cuts,
  - Mostly due to
    - early showering charged pions
    - Conversions: $\pi^0 \rightarrow \gamma\gamma \rightarrow ee+X$
    - Semileptonic b-decays
  - Difficult to model in MC
    - Hard fragmentation
    - Detailed simulation of calorimeter and tracking volume
- Measured in inclusive jet data at various E_T thresholds
  - Prompt electron content negligible:
    - N_{jet}~10 billion at 50 GeV!
  - Fake rate per jet:
    - CDF, tight cuts: 1/10000
    - ATLAS, tight cuts: 1/80000
  - Typical uncertainties 50%



Jets faking “loose” electrons

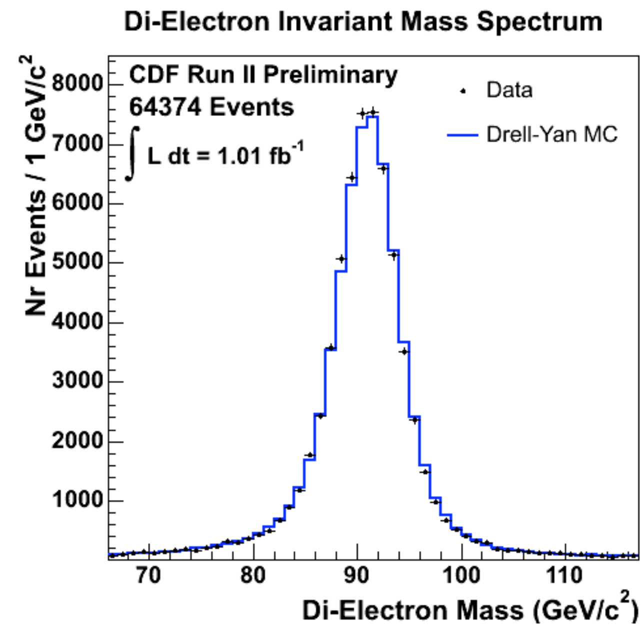


W's and Z's

- Z mass reconstruction
  - Invariant mass of two leptons

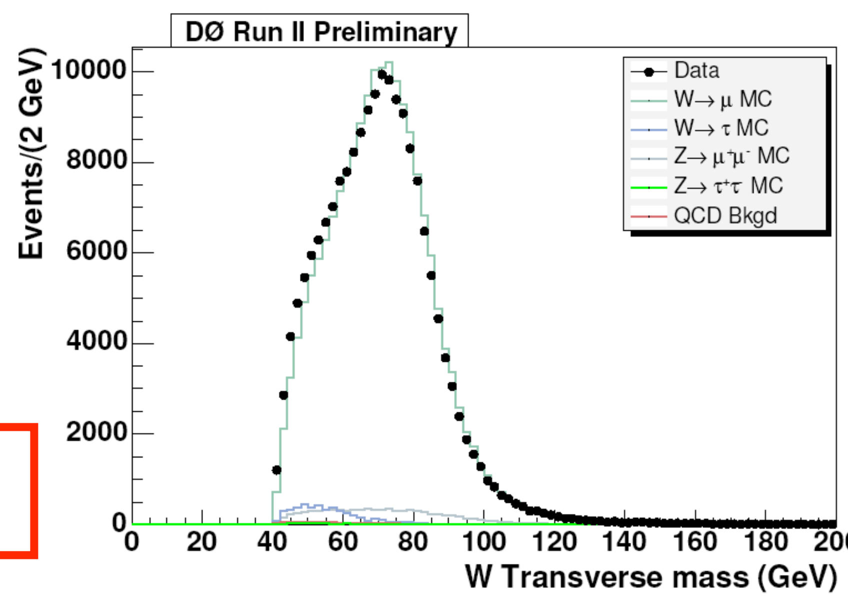
$$\boxed{m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}}$$

  - Sets electron energy scale by comparison to LEP measured value



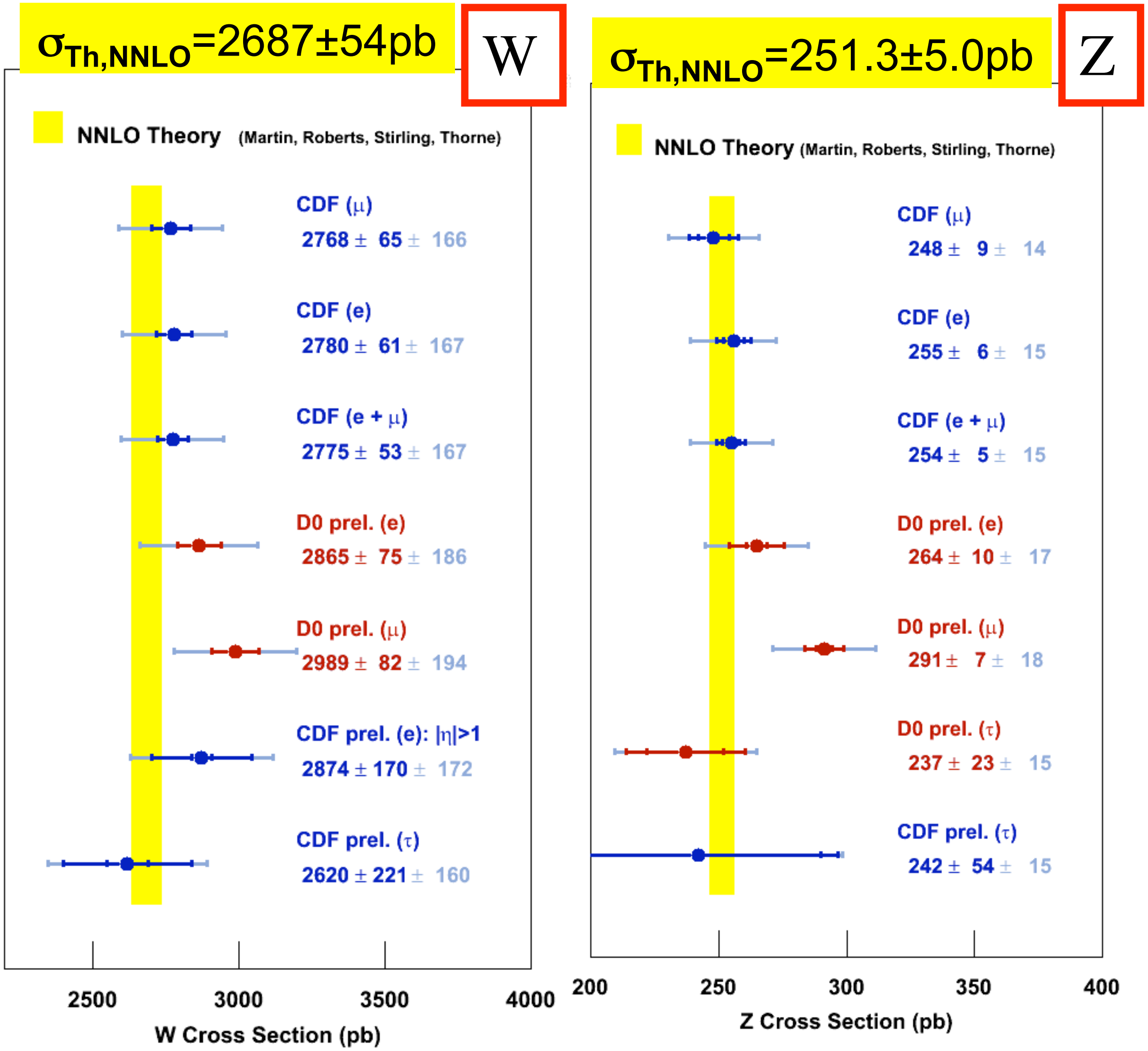
- W mass reconstruction
  - Do not know neutrino p_Z
  - No full mass resonstruction possible
  - Transverse mass:

$$\boxed{m_T = \sqrt{|p_T^\ell|^2 + |p_T^\nu|^2 - (\vec{p}_T^\ell + \vec{p}_T^\nu)^2}}$$

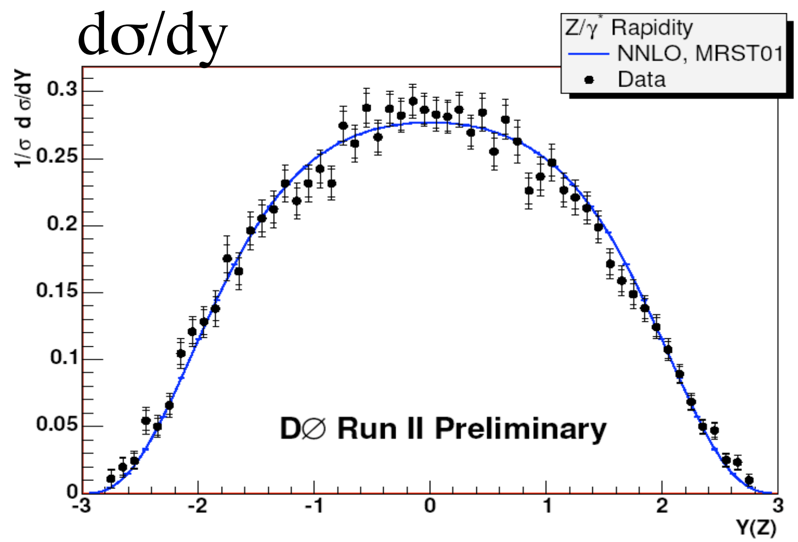


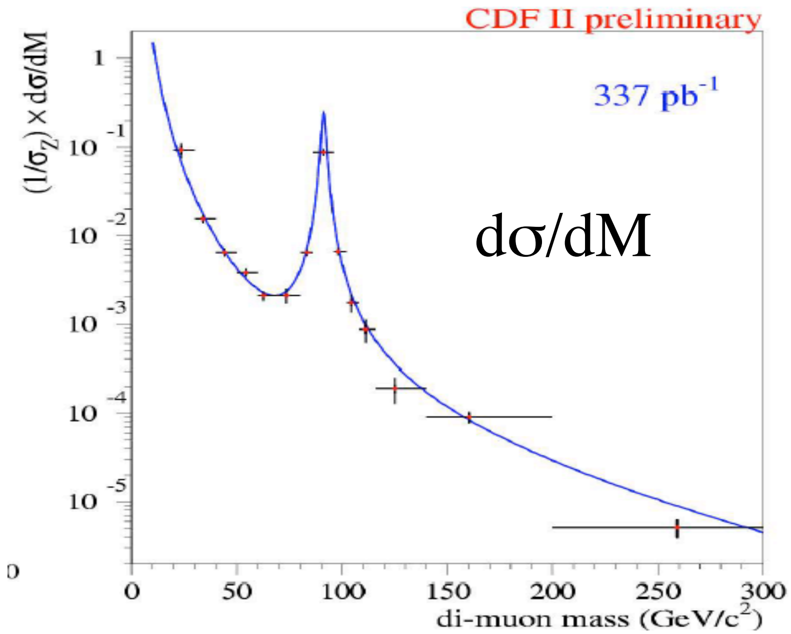
Tevatron W and Z Cross Section Results

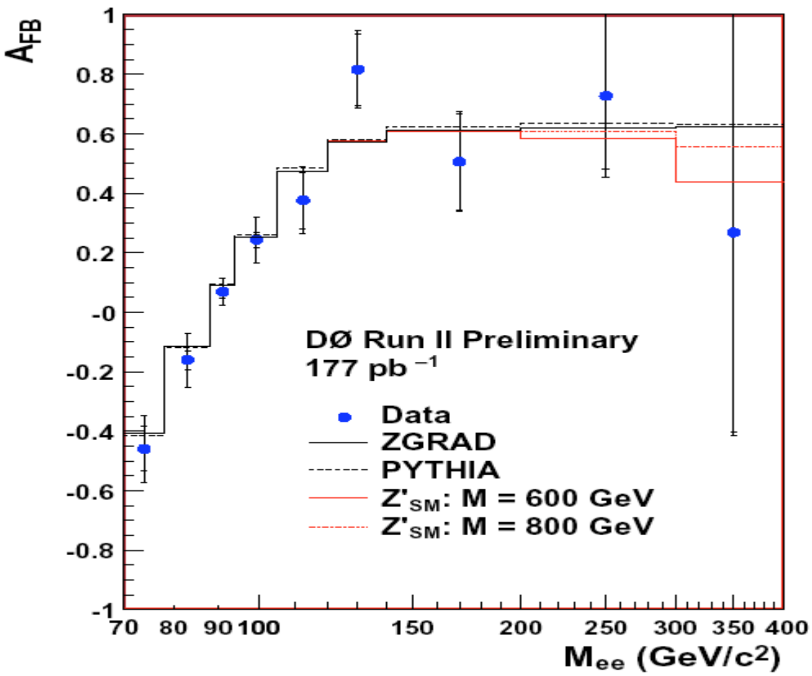
- Uncertainties:
  - Experimental: 2%
  - Theortical: 2%
  - Luminosity: 6%
- Can we use these processes to normalize luminosity?
  - Is theory reliable enough?

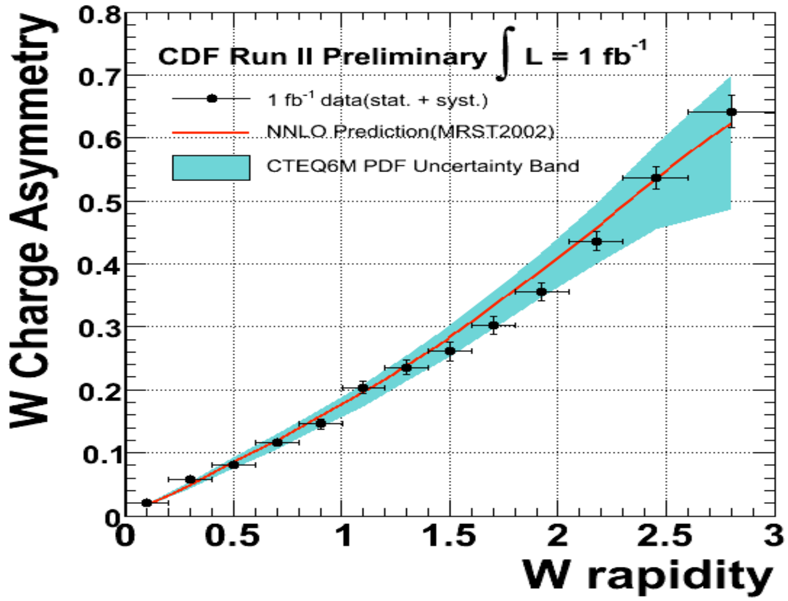


More Differential W/Z Measurements

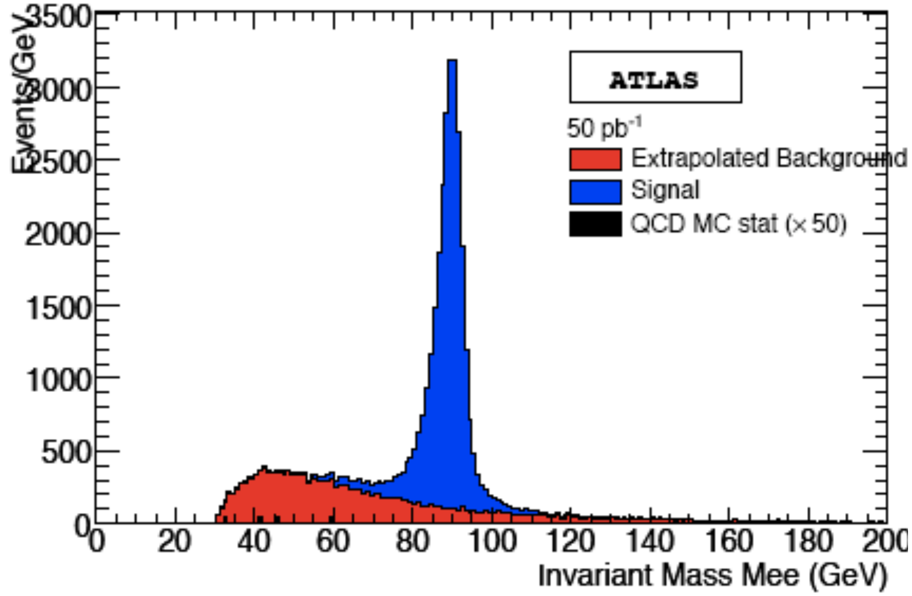


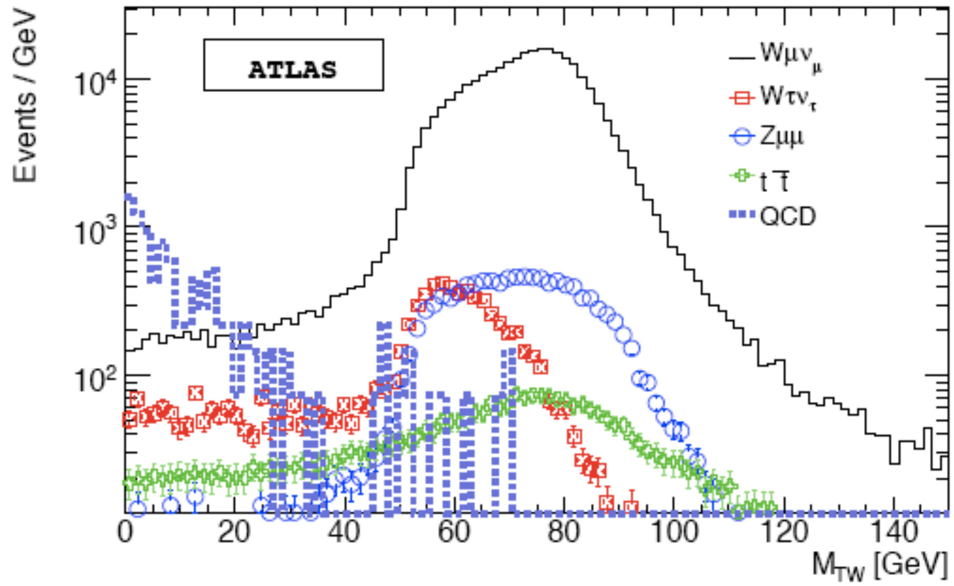




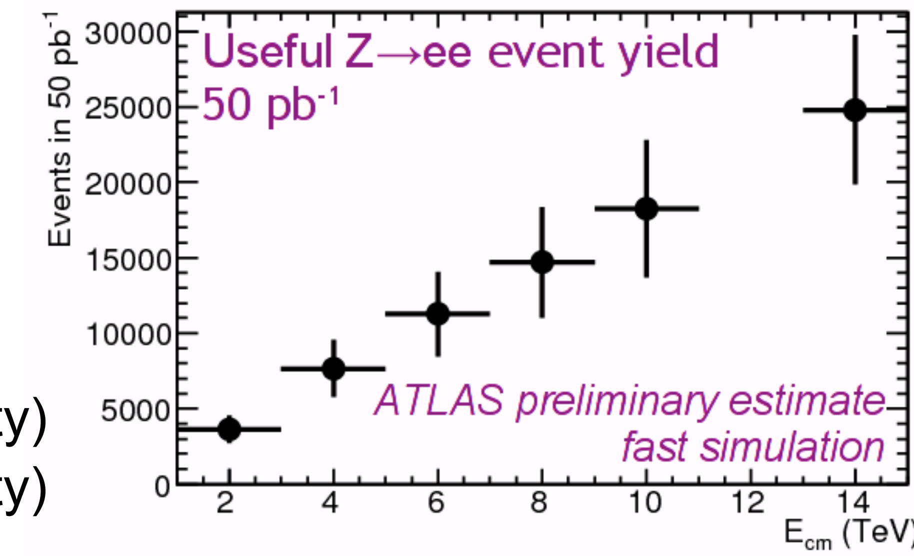


LHC signals of W's and Z's with 50 pb^{-1}





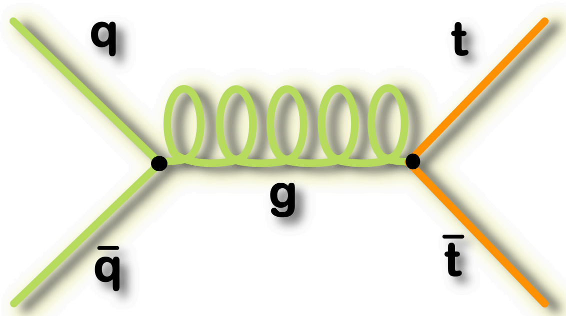
- 50 pb^{-1} yield clean signals
  - Factor ~2 smaller yield at 7 TeV
- Experimental precision
  - ~5% for 50 pb^{-1} $\oplus$ ~10% (luminosity)
  - ~2.5% for 1 fb^{-1} $\oplus$ ~10% (luminosity)

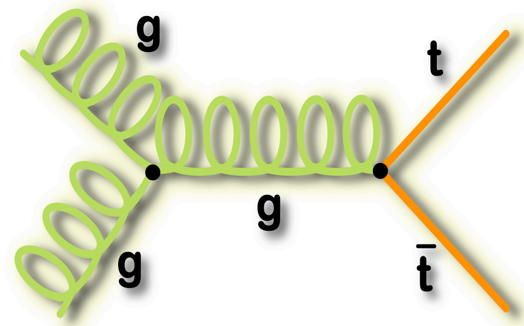


Top Quark Production and Decay

- At Tevatron, mainly produced in pairs via the strong interaction

85%





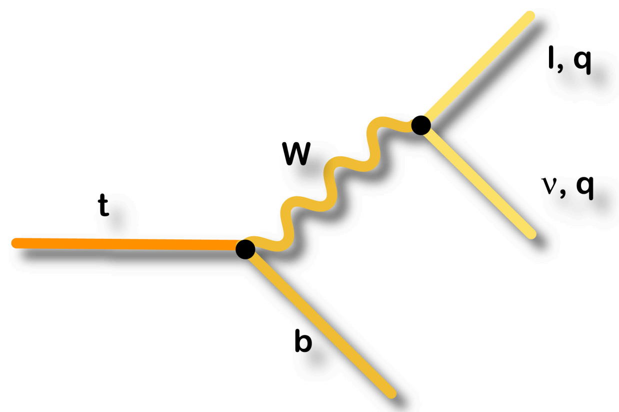
15%

- Decay via the electroweak interactions **Br($t \rightarrow Wb$) ~ 100%**
  Final state is characterized by the decay of the W boson

Dilepton

Lepton+Jets

All-Jets



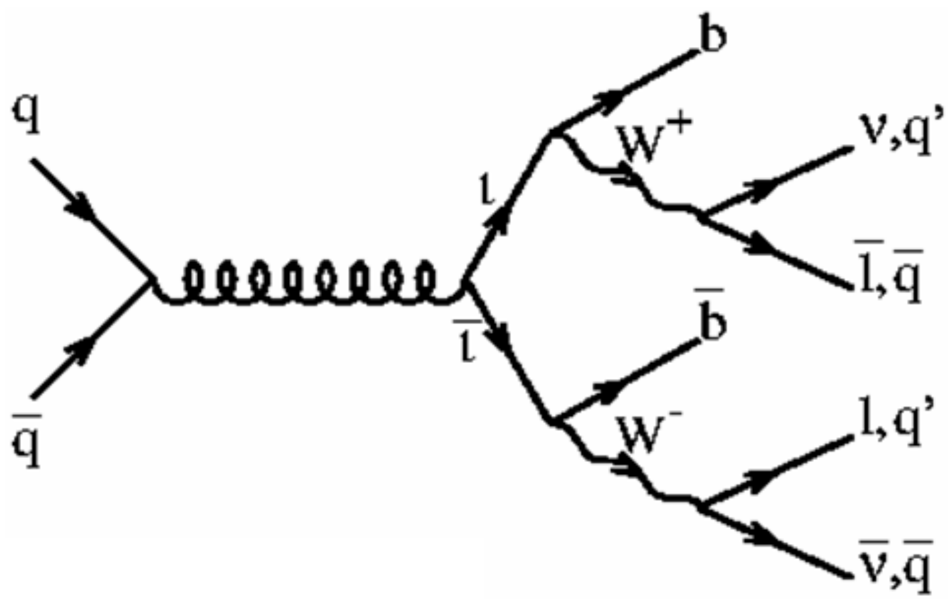
Different sensitivity and challenges in each channel

How to identify the top quark

SM: $t\bar{t}$ pair production, Br($t \rightarrow bW$)=100% , Br($W \rightarrow l\nu$)=1/9=11%

dilepton	***(4/81)***	**2 leptons + 2 jets + missing E_T**
l+jets	***(24/81)***	**1 lepton + 4 jets + missing E_T**
fully hadronic	***(36/81)***	**6 jets**

(here: l=e,μ)



How to identify the top quark

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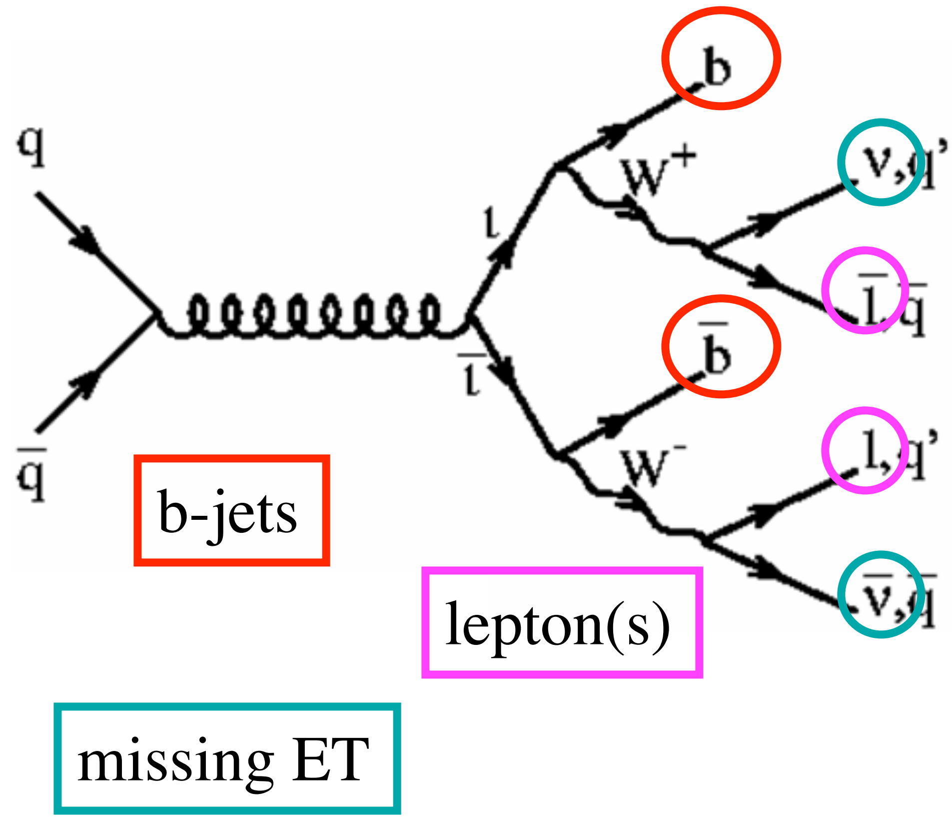
dilepton	***(4/81)***	**2 leptons + 2 jets + missing E_T**
lepton+jets	***(24/81)***	**1 lepton + 4 jets + missing E_T**
fully hadronic	***(36/81)***	**6 jets**



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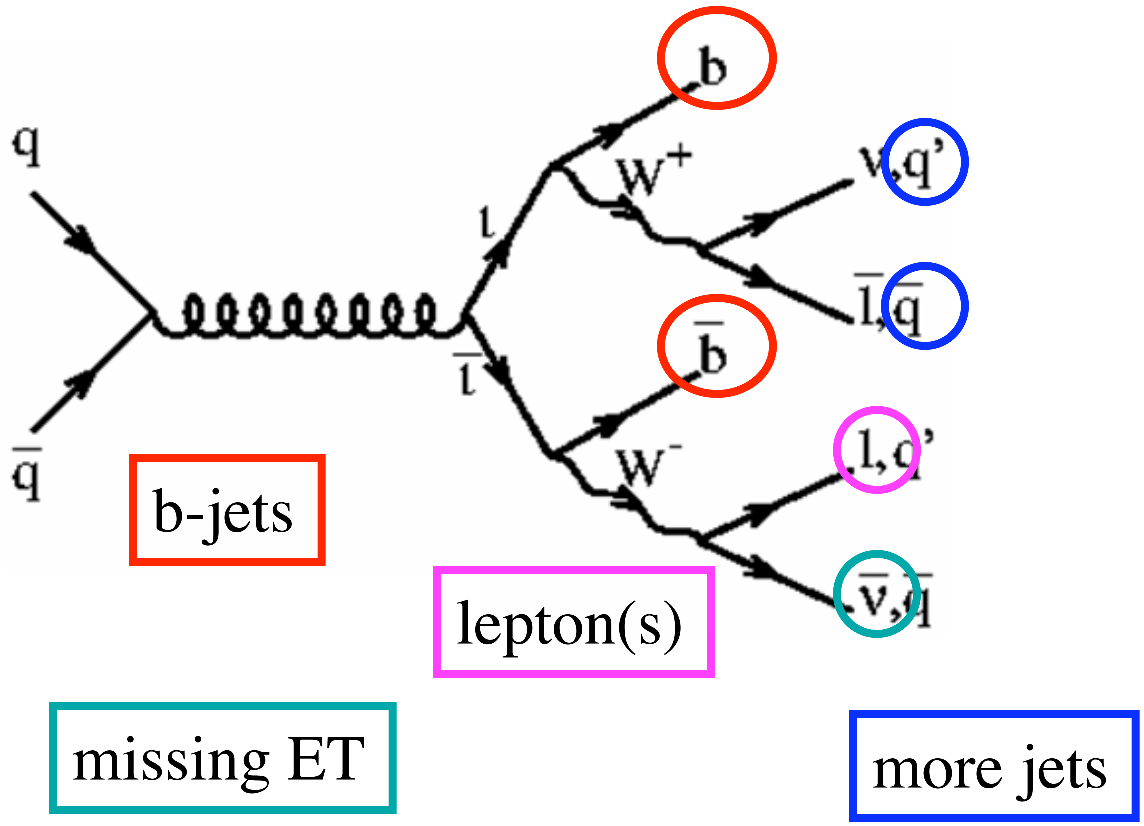

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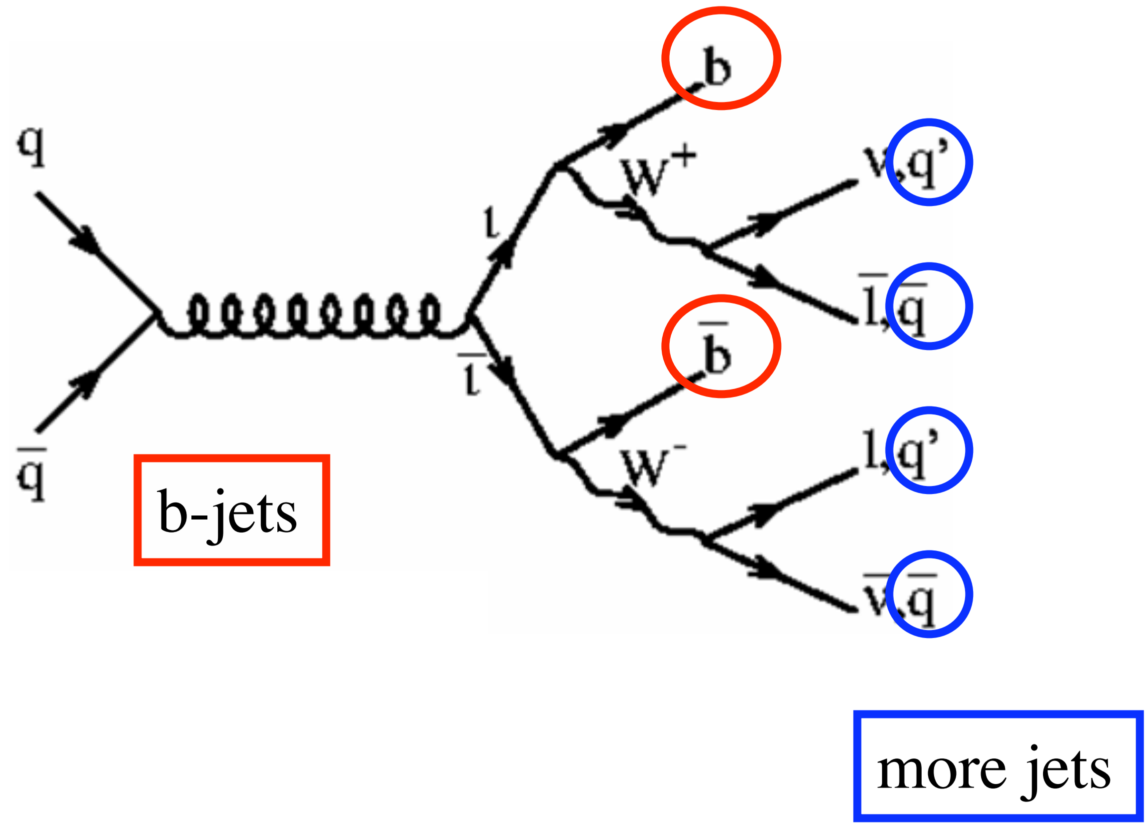
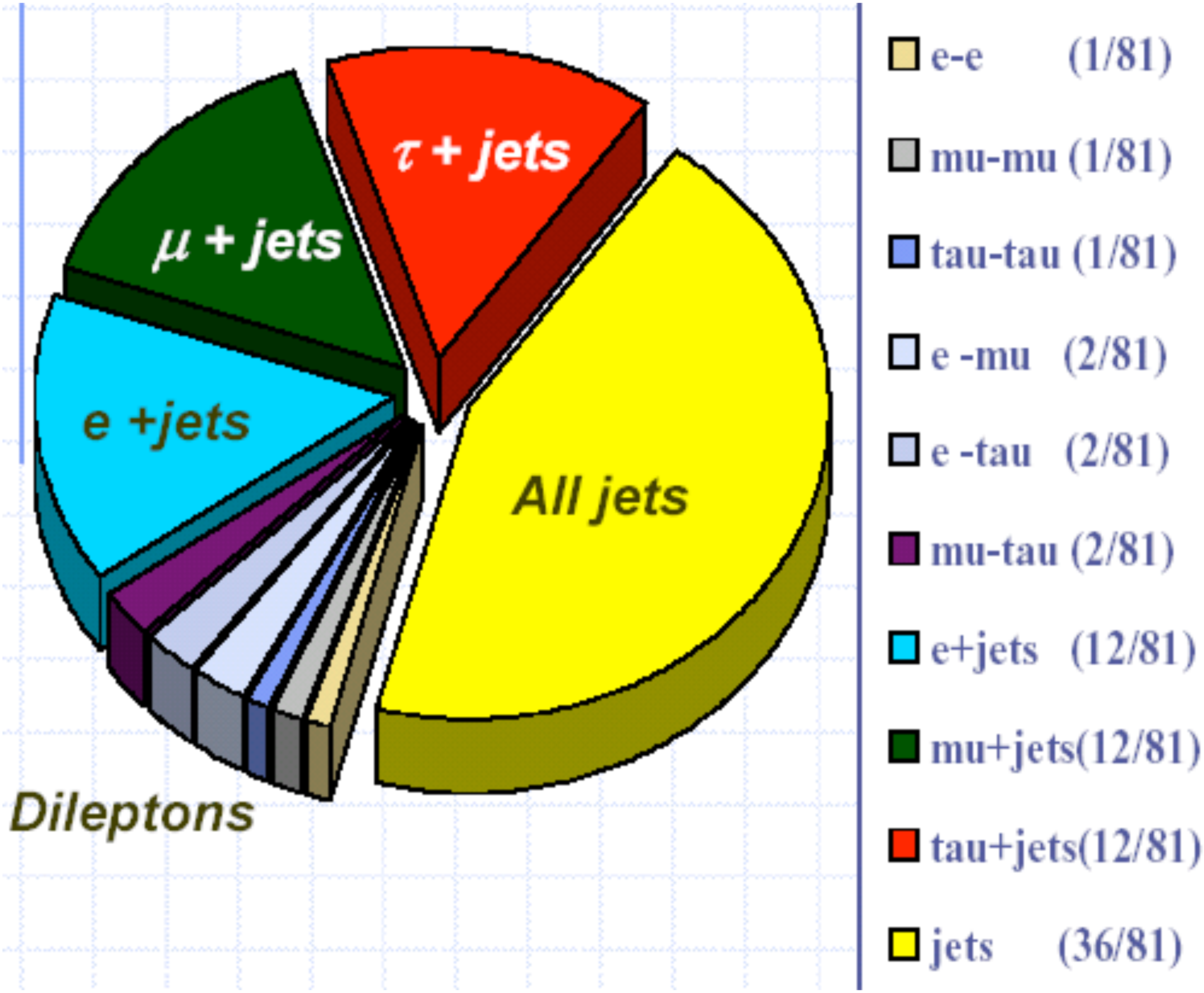
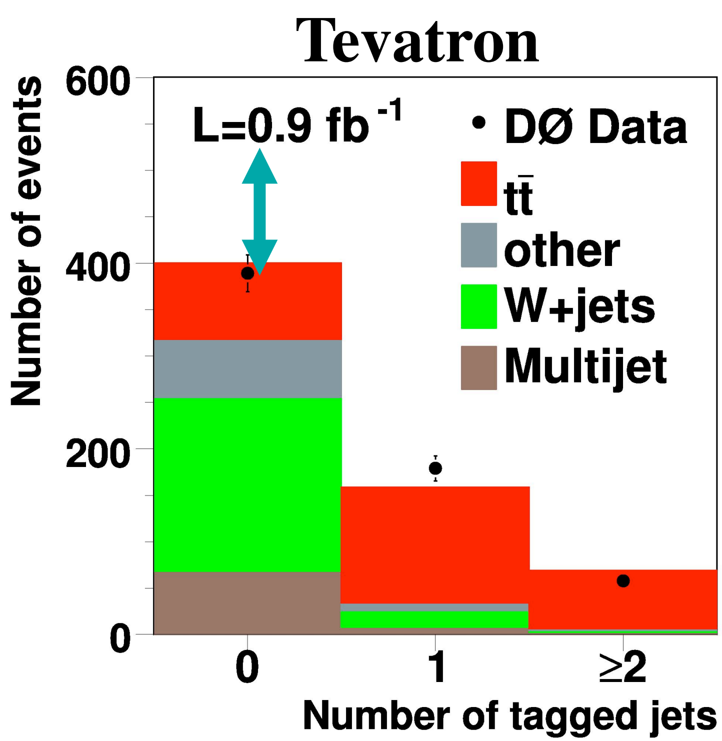
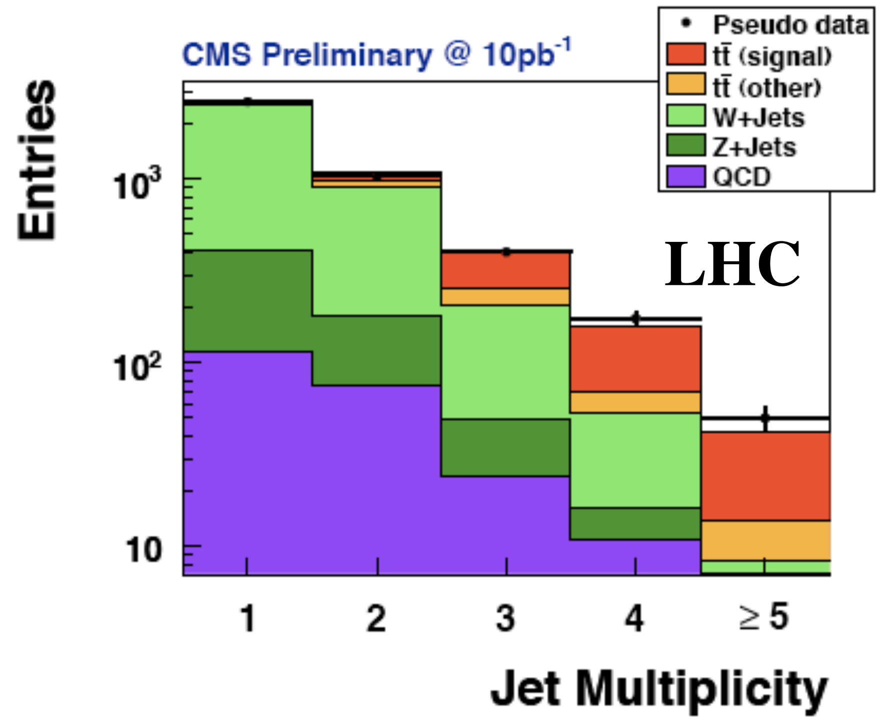


Top Event Categories



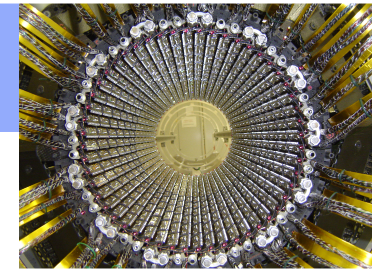
Finding the Top at Tevatron and LHC without b-quark identification



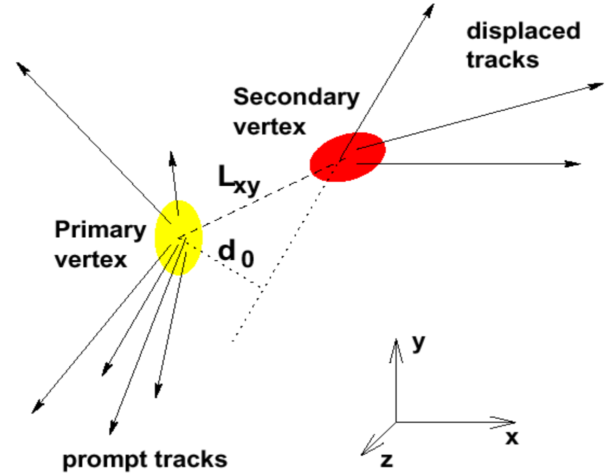


- Tevatron:
  - Top is overwhelmed by backgrounds:
  - Even for 4 jets S/B is only about 0.8
  - Use b-jets to purify sample
- LHC
  - Signal clear even without b-tagging: S/B is about 1.5-2

Finding the b-jets



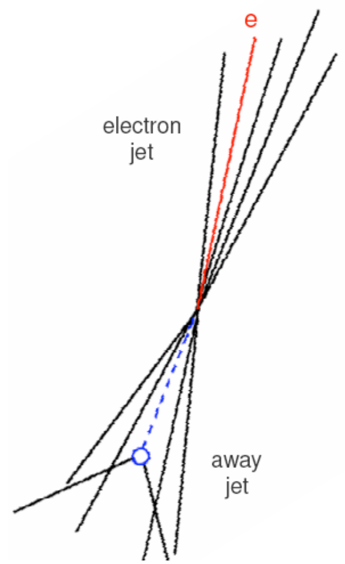
- Exploit large lifetime of the b-hadron
  - B-hadron flies before it decays: $d=c\tau$
    - Lifetime τ =1.5 ps^{-1}
    - $d=c\tau$ = 460 μm
    - Can be resolved with silicon detector resolution

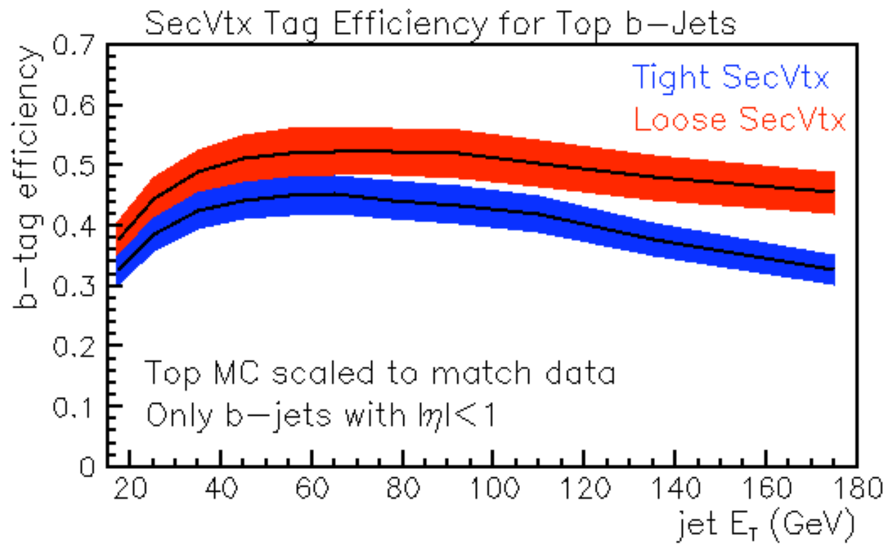


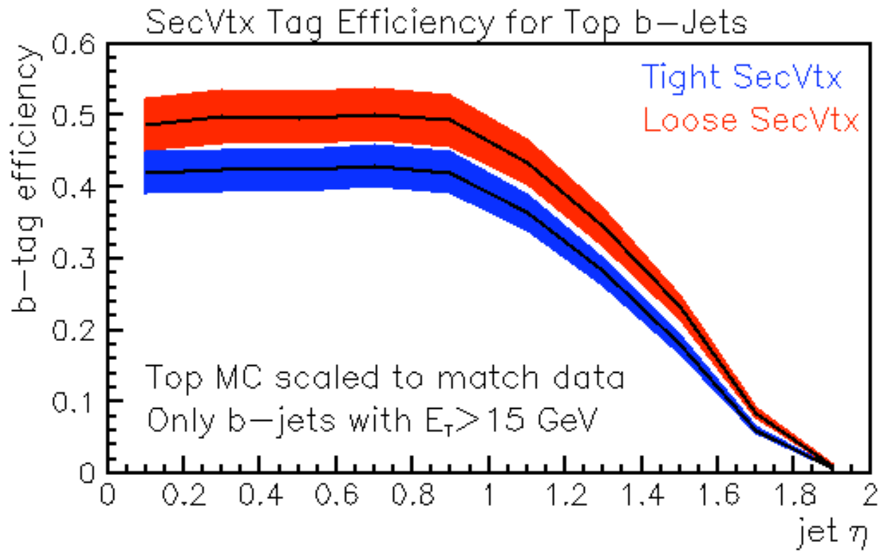
- Procedure “Secondary Vertex”:
  - reconstruct primary vertex:
    - resolution ~ 30 μm
  - Search tracks inconsistent with primary vertex (large d_0):
    - Candidates for secondary vertex
    - See whether three or two of those intersect at one point
  - Require displacement of secondary from primary vertex
    - Form L_{xy}: transverse decay distance projected onto jet axis:
      - $L_{xy}>0$: b-tag along the jet direction => real b-tag or mistag
      - $L_{xy}<0$: b-tag opposite to jet direction => mistag!
    - Significance: e.g. $\delta L_{xy} / L_{xy} > 7$ (i.e. 7σ significant displacement)
- More sophisticated techniques exist

Characterise the B-tagger: Efficiency

- Efficiency of tagging a true b-jet
  - Use Data sample enriched in b-jets
  - Select jets with electron or muons
    - From semi-leptonic b-decay
  - Measure efficiency in data and MC



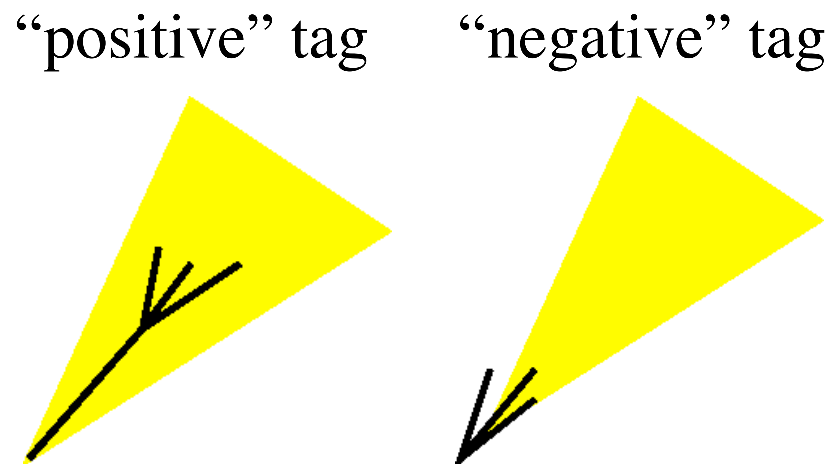


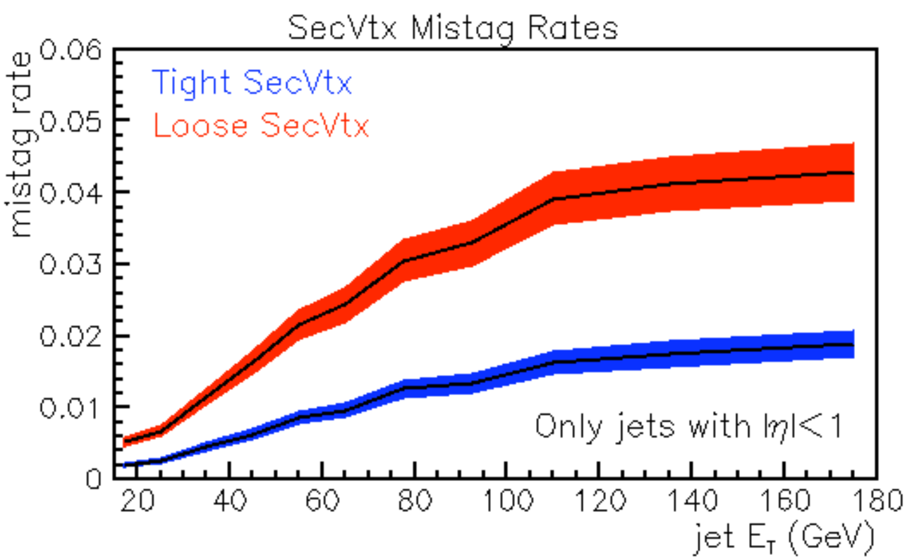


Achieve efficiency of about 40-50% at Tevatron

Characterise the B-tagger: Mistag rate

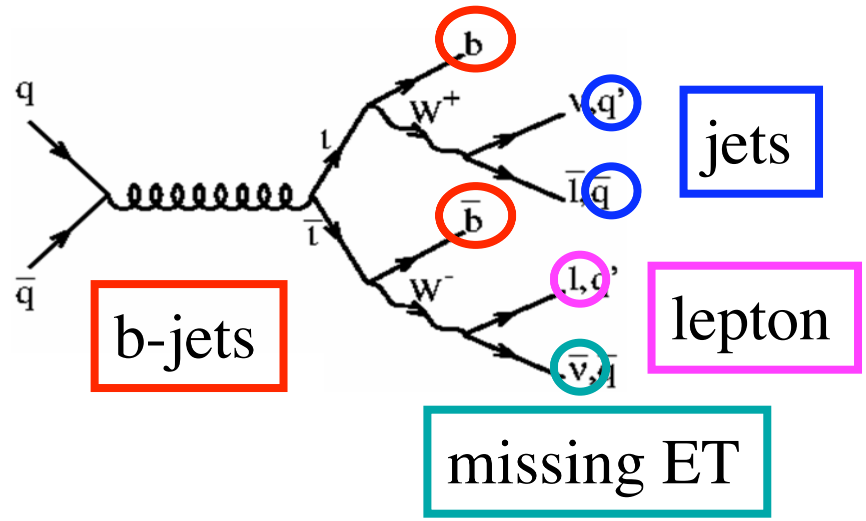
- Mistag Rate measurement:
  - Probability of light quarks to be misidentified
  - Use "negative" tags: L_{xy}<0
    - Can only arise due to misreconstruction
  - Mistag rate for E_T=50 GeV:
    - Tight: 0.5% (ε=43%)
    - Loose: 2% (ε=50%)
  - Depending on physics analyses:
    - Choose "tight" or "loose" tagging algorithm

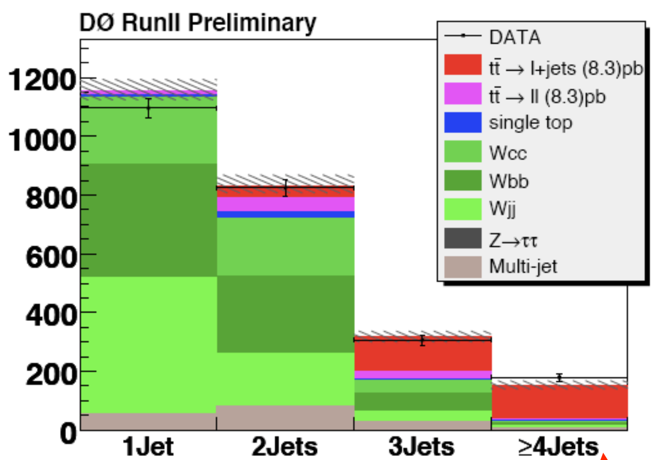


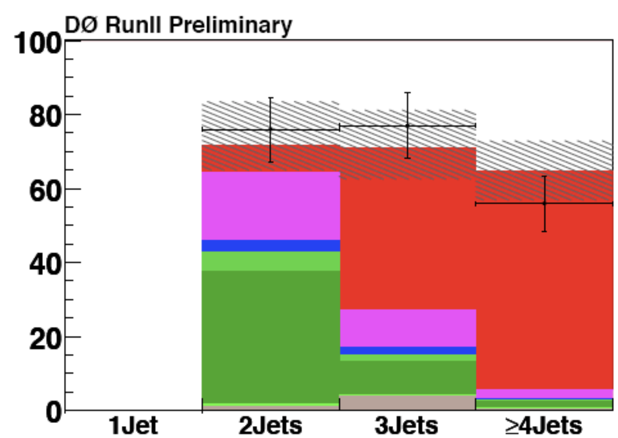


The Top Signal: Lepton + Jets

- Select:
  - 1 electron or muon
  - Large missing E_T
  - 1 or 2 b-tagged jets







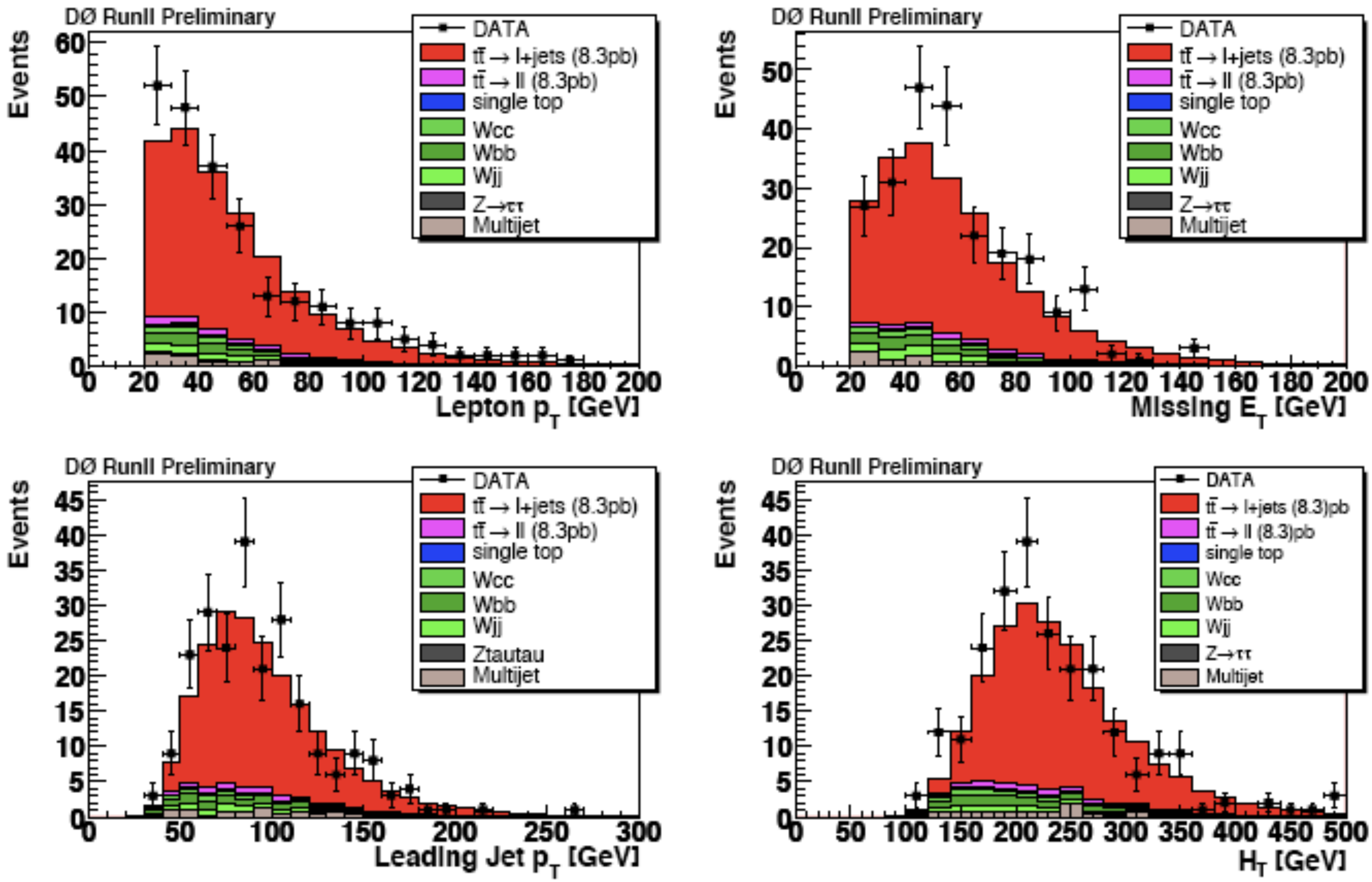
double-tagged events, nearly no background

Check backgrounds

Top Signal

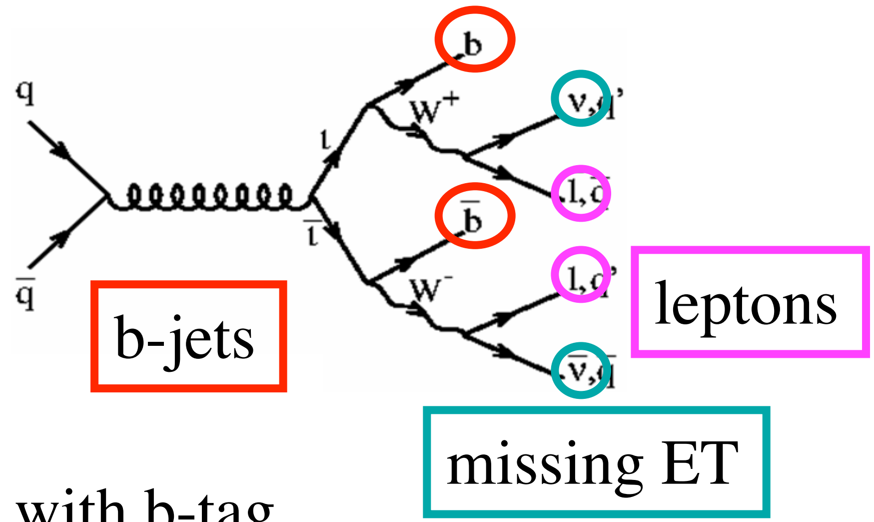
$\sigma(t\bar{t}) = 8.3^{+0.6}_{-0.5}(\text{stat}) \pm 1.1\ (\text{syst})\ \text{pb}$

Data and Monte Carlo Comparison

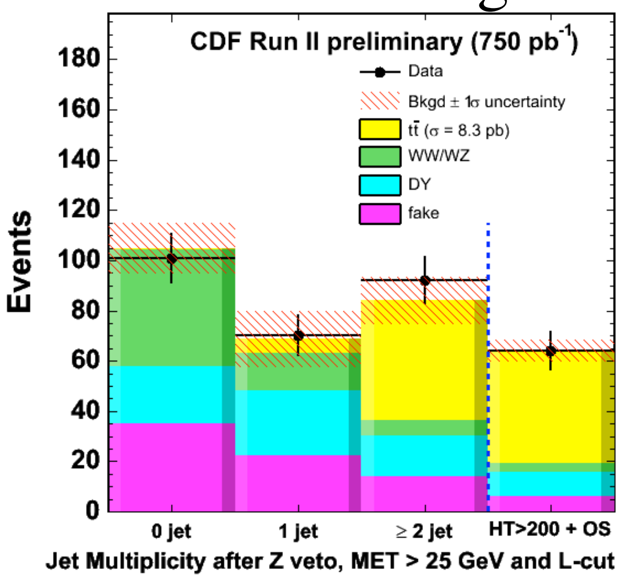


The Top Signal: Dilepton

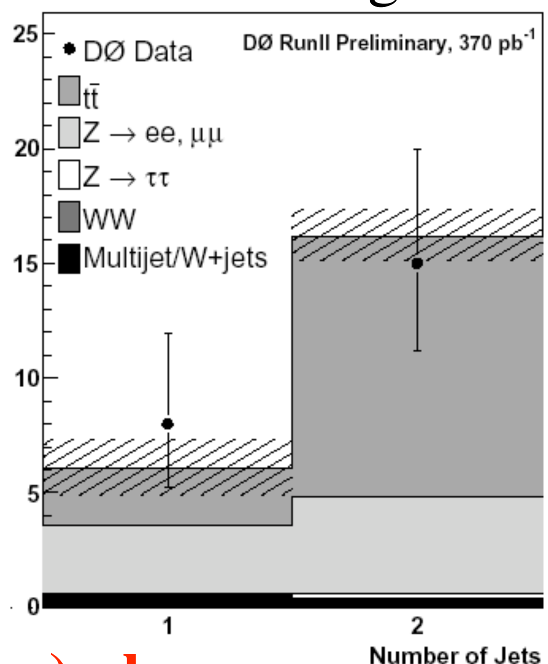
- Select:
  - 2 leptons: ee, eμ, μμ
  - Large missing E_T
  - 2 jets (with or w/o b-tag)



w/o b-tag

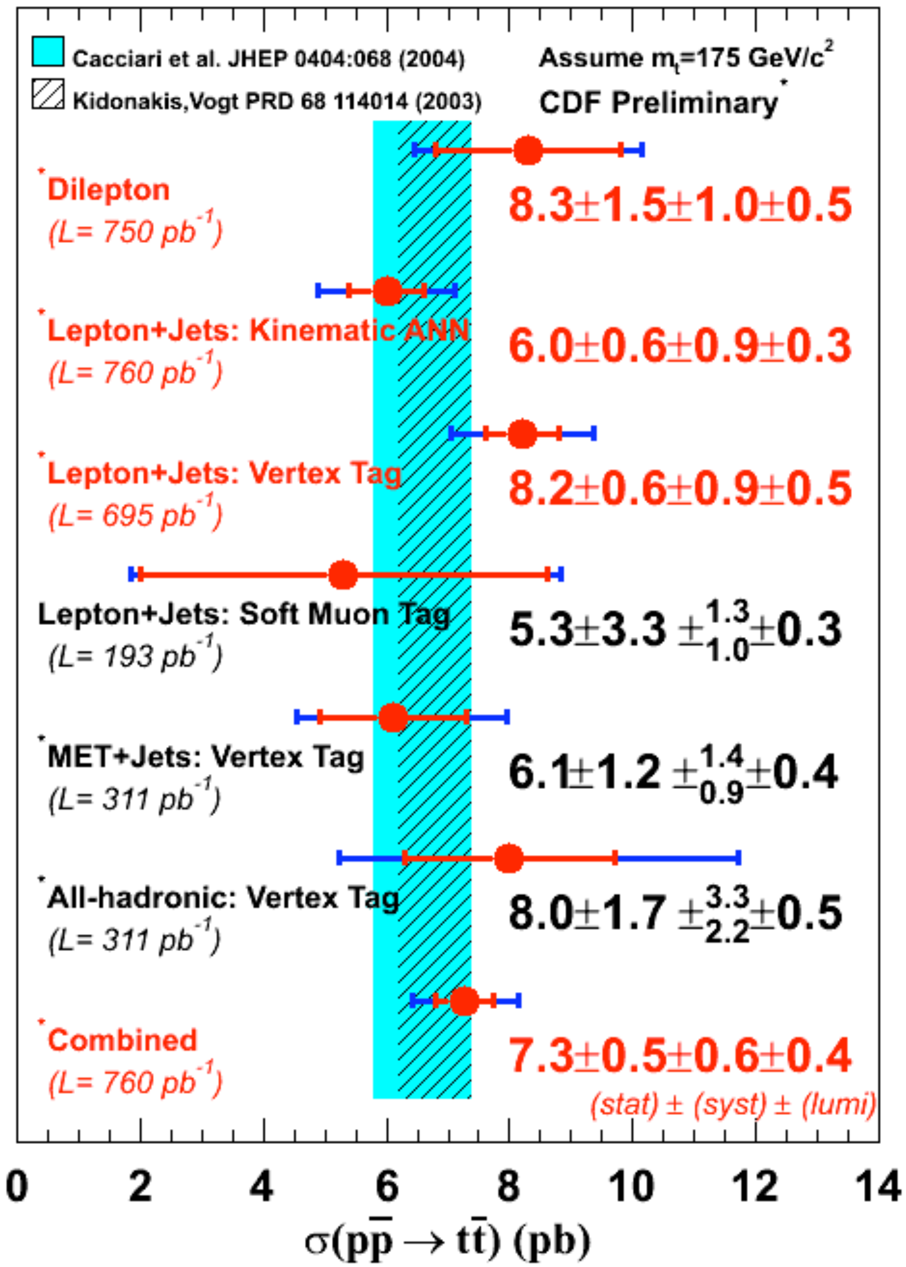


with b-tag



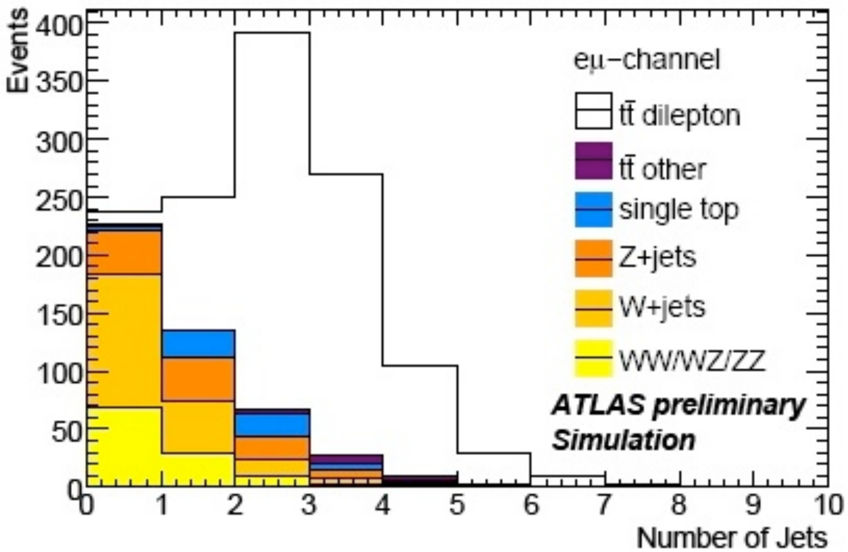
$\sigma = 6.2 \pm 0.9\ (\text{stat}) \pm 0.9\ (\text{sys})$ pb

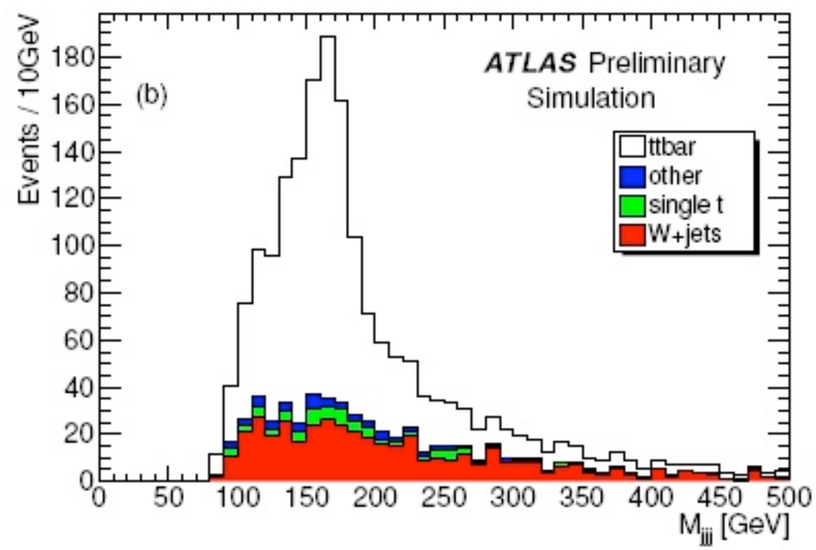
The Top Cross Section



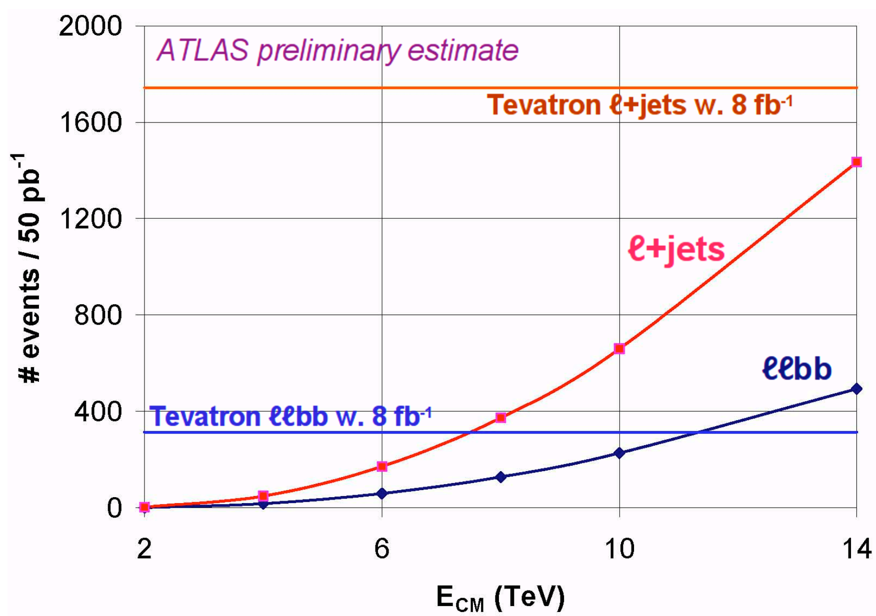
- **Tevatron**
  - Measured using many different techniques
  - Good agreement
    - between all measurements
    - between data and theory
  - Precision: ~13%
- **LHC:**
  - Cross section ~100 times larger
  - Measurement will be one of the first milestones (already with 10 pb^{-1})
    - Test prediction
    - demonstrate good understanding of detector
  - Expected precision
    - ~4% with 100 pb^{-1}

Top at LHC: very clean





- At √s=7 TeV:
  - About 200 pb^{-1} surpass Tevatron top sample statistics
  - About 20 pb^{-1} needed for "rediscovery"



Conclusions

- Hadron collisions are complex.
  - Cross sections determined by parton distribution functions
    - Strong rise of gluon towards low x
  - Many soft particles unrelated to hard scatter
    - Use transverse momentum (p_T) as major discriminant

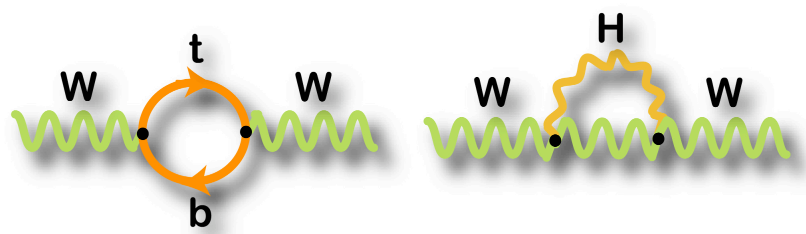
- Perturbative QCD describes hadron collider data successfully:
  - Jet cross sections: $\Delta\sigma/\sigma \approx$ 20-100%
  - W/Z cross section: $\Delta\sigma/\sigma \approx$ 6%
  - Top cross section: $\Delta\sigma/\sigma \approx$ 15%

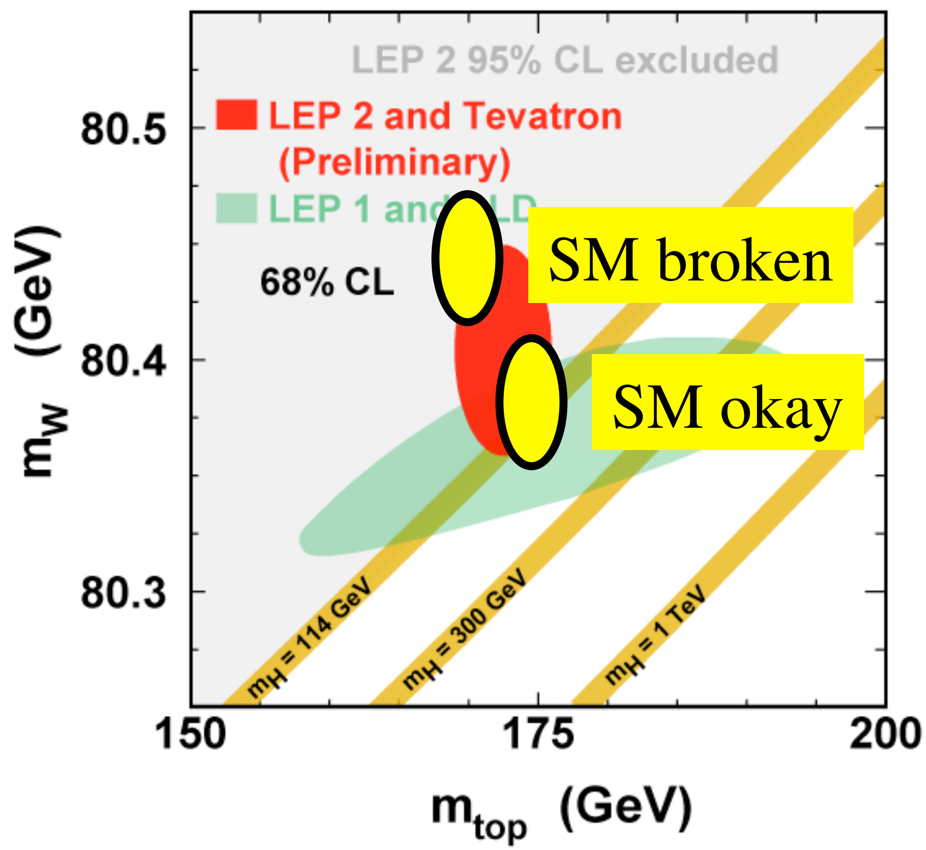
Precision Measurement of Electroweak Sector of the Standard Model

- W boson mass
- Top quark mass
- Implications for the Higgs boson

The W boson, the top quark and the Higgs boson

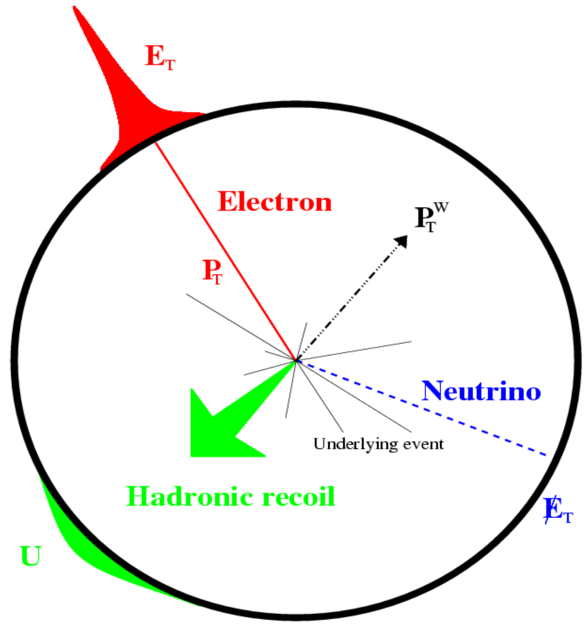
- Top quark is the heaviest known fundamental particle
  - Today: m_{top}=173.1+-1.3 GeV
  - Run 1: m_{top}=178+-4.3 GeV/c^2
  - Is this large mass telling us something about electroweak symmetry breaking?
    - Top yukawa coupling:
    - $\langle H \rangle/(\sqrt{2}\, m_{top}) = 1.005 \pm 0.008$
- Masses related through radiative corrections:
  - $m_W \sim M_{top}^2$
  - $m_W \sim \ln(m_H)$
- If there are new particles the relation might change:
  - Precision measurement of top quark and W boson mass can reveal new physics





W Boson mass

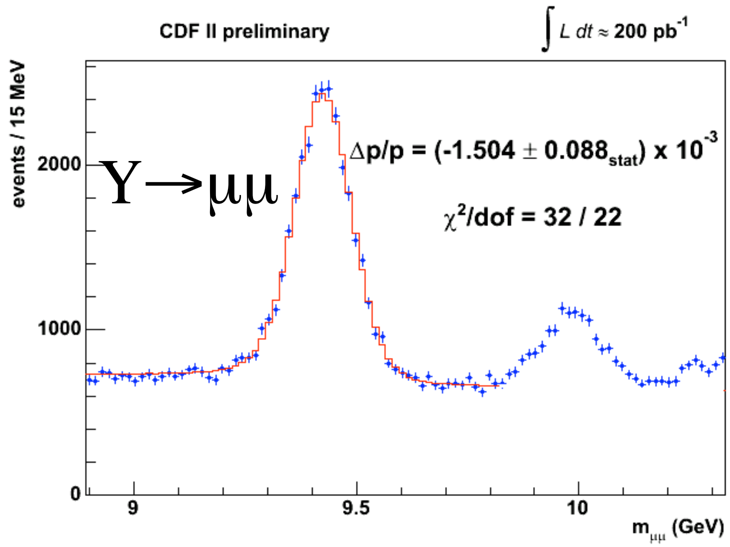
- Real precision measurement:
  - LEP: M_W=80.367±0.033 GeV/c^2
  - Precision: 0.04%
    - => Very challenging!
- Main measurement ingredients:
  - Lepton p_T
  - Hadronic recoil parallel to lepton: $u_{||}$
- Z→ll superb calibration sample:
  - but statistically limited:
    - About a factor 10 less Z's than W's
    - Most systematic uncertainties are related to size of Z sample
      - Will scale with $1/\sqrt{N_Z}$ ($=1/\sqrt{L}$)

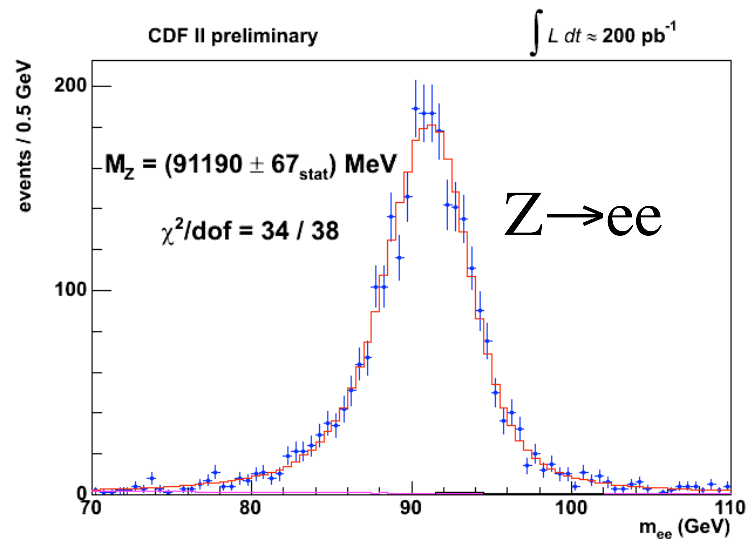


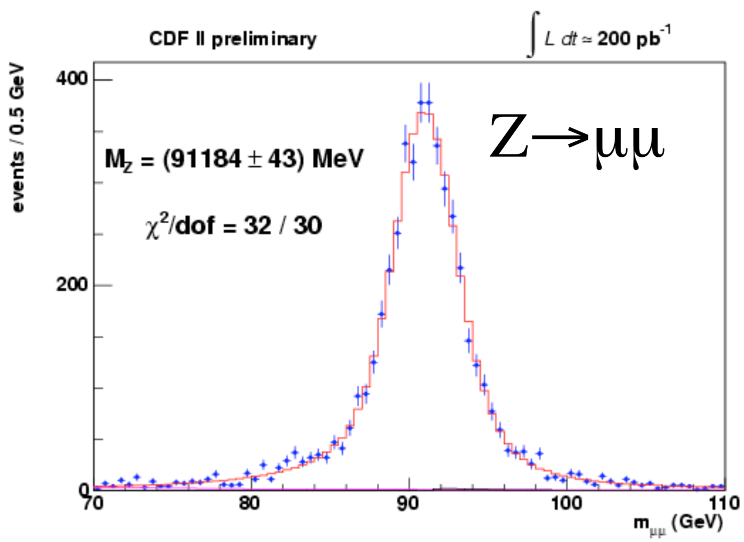
$$m_T = \sqrt{2 p_T^l \not{p}_T \, (1 - \cos\Delta\phi)},$$
$$\not{p}_T \approx |p_T + u_{||}|$$

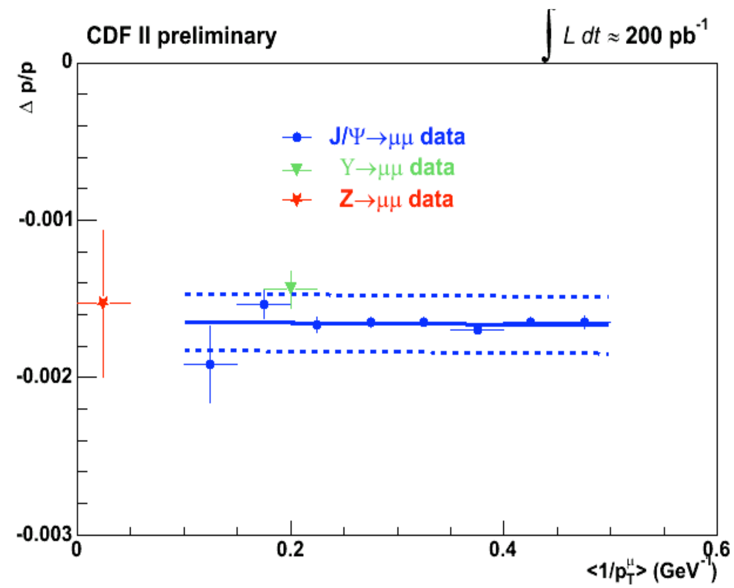
$$\boxed{m_T \approx 2p_T\sqrt{1 + u_{||}/p_T} \approx 2p_T + u_{||}}$$

Lepton Momentum Scale and Resolution









- **Systematic uncertainty on momentum scale: 0.04%**

Systematic Uncertainties

m_T Fit Uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Correlation
Tracker Momentum Scale	17	17	100%
Calorimeter Energy Scale	0	25	0%
Lepton Resolution	3	9	0%
Lepton Efficiency	1	3	0%
Lepton Tower Removal	5	8	100%
Recoil Scale	9	9	100%
Recoil Resolution	7	7	100%
Backgrounds	9	8	0%
PDFs	11	11	100%
W Boson p_T	3	3	100%
Photon Radiation	12	11	100%
Statistical	54	48	0%
Total	60	62	-

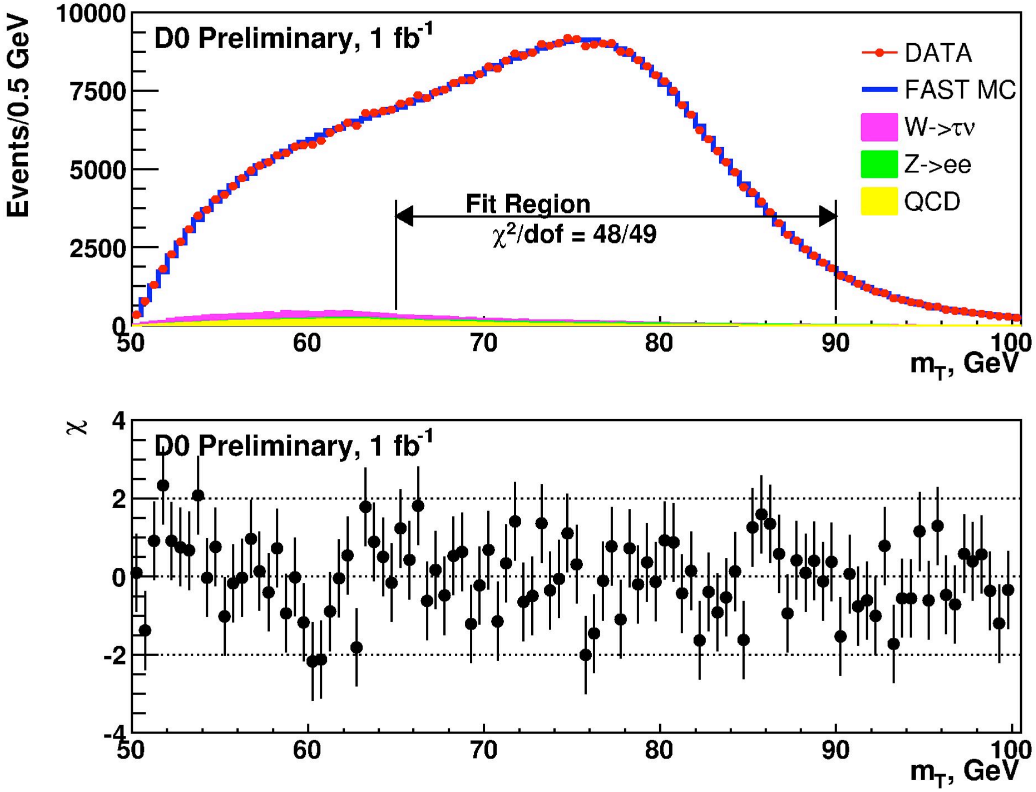
Limited by data statistics

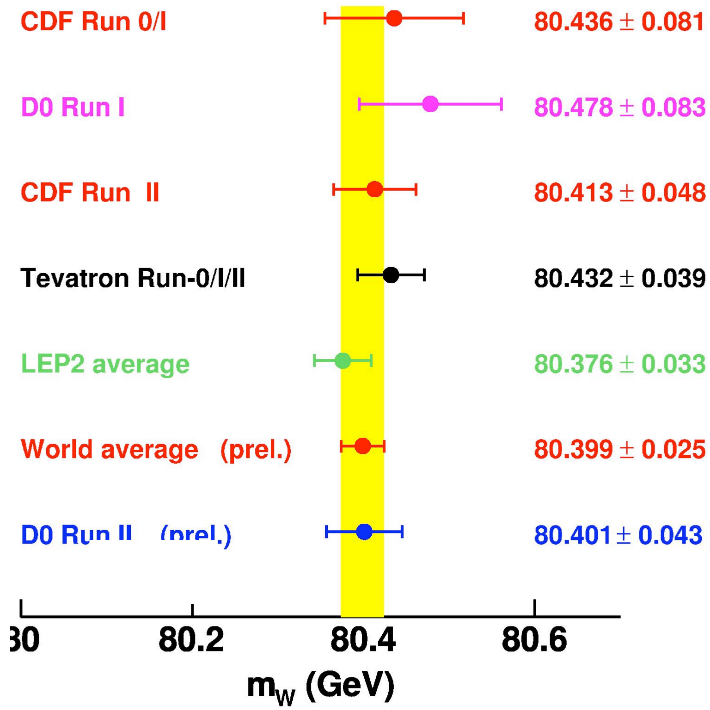
Limited by data and theoretical understanding

TABLE IX: Uncertainties in units of MeV on the transverse mass fit for m_W in the $W \to \mu\nu$ and $W \to e\nu$ samples.

- Overall uncertainty 60 MeV for both analyses
  - Careful treatment of correlations between them
- Dominated by stat. error (50 MeV) vs syst. (33 MeV)

W Boson Mass





New world average:

M_W=80399 ± 23 MeV

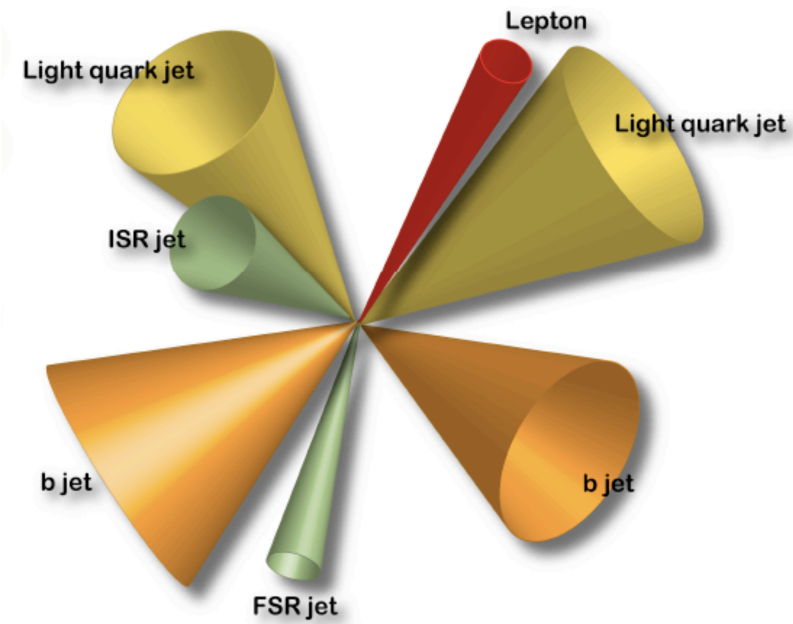
Ultimate precision:

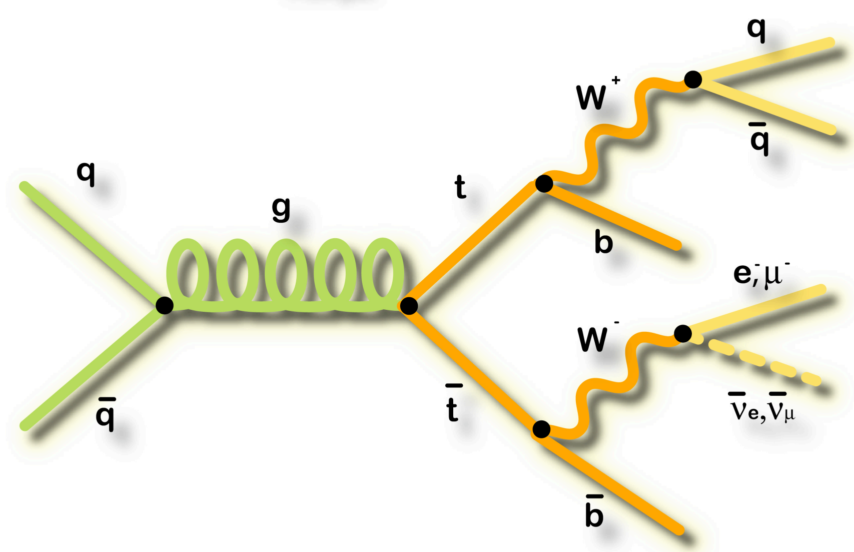
Tevatron: 15-20 MeV

LHC: unclear (5 MeV?)

Top Mass Measurement: $tt \rightarrow (bl\nu)\,(bqq)$

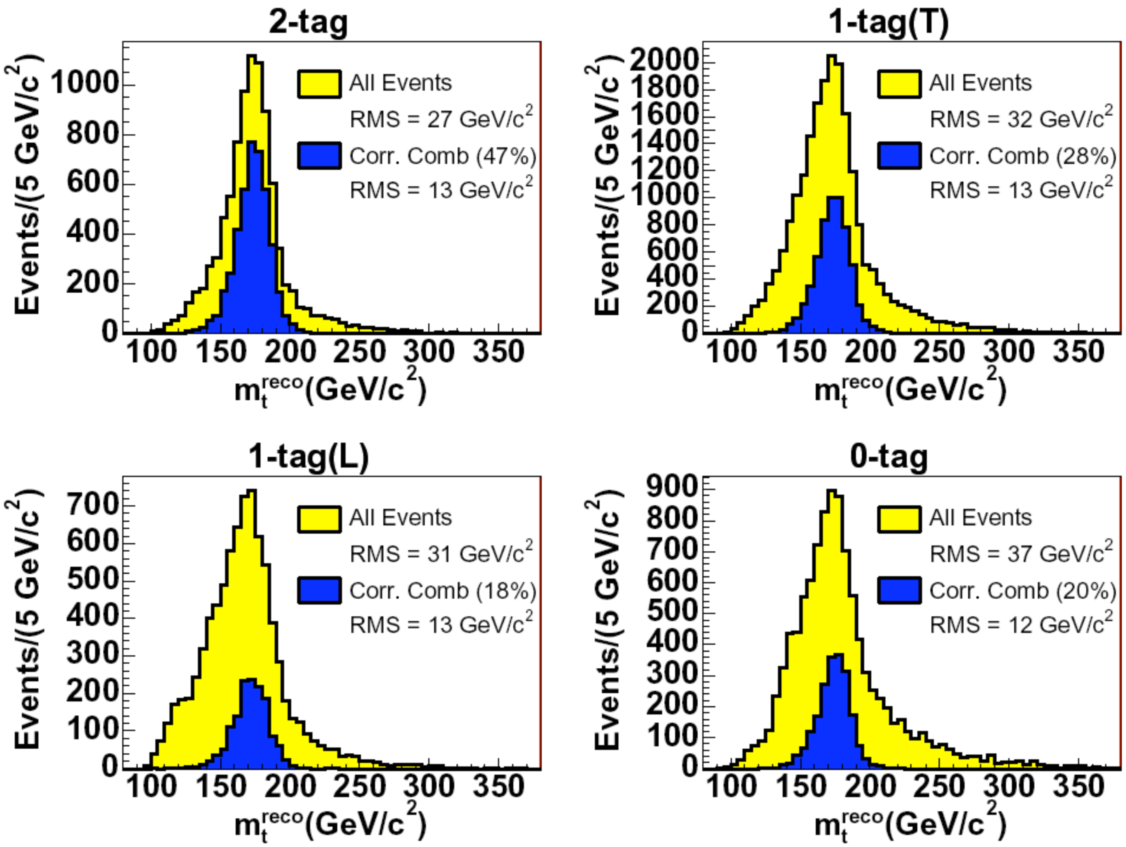
- 4 jets, 1 lepton and missing E_T
  - Which jet belongs to what?
  - Combinatorics!
- B-tagging helps:
  - 2 b-tags =>2 combinations
  - 1 b-tag => 6 combinations
  - 0 b-tags =>12 combinations
- Two Strategies:
  - Template method:
    - Uses "best" combination
    - Chi2 fit requires $m(t)=m(\bar{t})$
  - Matrix Element method:
    - Uses all combinations
    - Assign probability depending on kinematic consistency with top





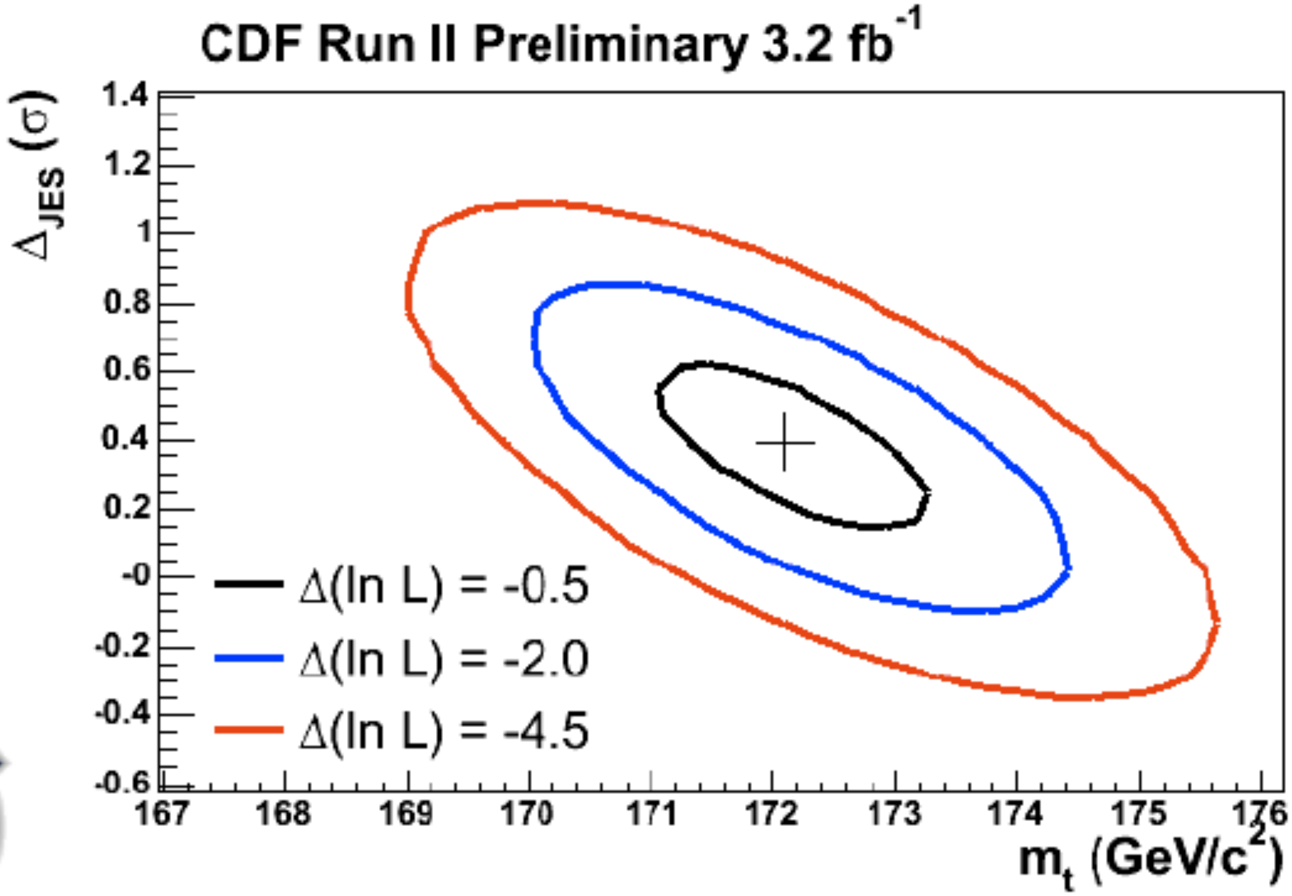
Top Mass Determination

- Inputs:
  - Jet 4-vectors
  - Lepton 4-vector
  - Remaining transverse energy, $p_{T,UE}$:
    - $p_{T,\nu}=-(p_{T,l}+p_{T,UE}+\sum p_{T,jet})$
- Constraints:
  - $M(l\nu)=M_W$
  - $M(q\overline{q})=M_W$
  - $M(t)=M(\overline{t})$
- Unknown:
  - Neutrino p_z
- 1 unknown, 3 constraints:
  - Overconstrained
  - Can measure M(t) for each event: m_t^{reco}
  - Leave jet energy scale ("JES") as free parameter



Selecting correct combination
20-50% of the time

Example Results on m_{top}



m_{top} =
173.7 ± 0.8 (stat) ± 1.6 (syst) GeV

3.6 fb^{-1}

±1.0%

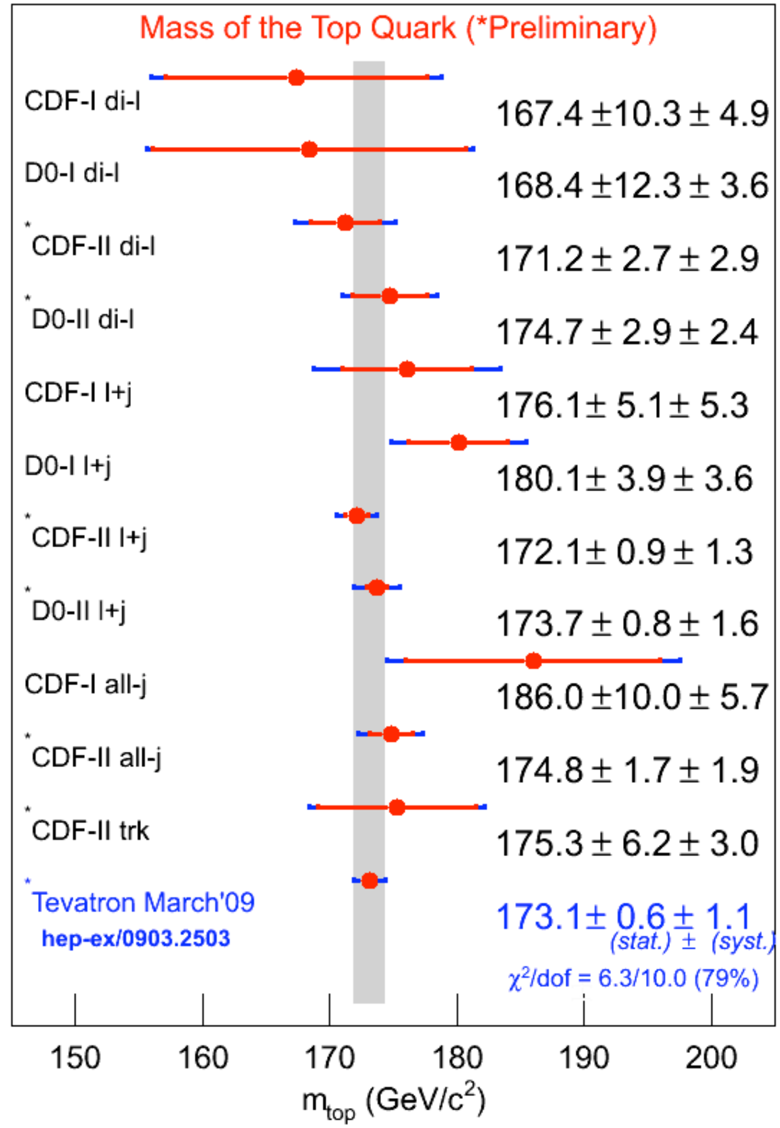
m_{top} =
172.1 ± 0.9 (stat) ± 1.3 (syst) GeV

3.2 fb^{-1}

±0.9%

Combining M_{top} Results

- Excellent results in each channel
  - Dilepton
  - Lepton+jets
  - All-hadronic
- Combine them to improve precision
  - Include Run-I results
  - Account for correlations
- **Uncertainty: 1.3 GeV**
  - Dominated by syst. uncertainties
- Precision so high that theorists wonder about what it's exact definition is!

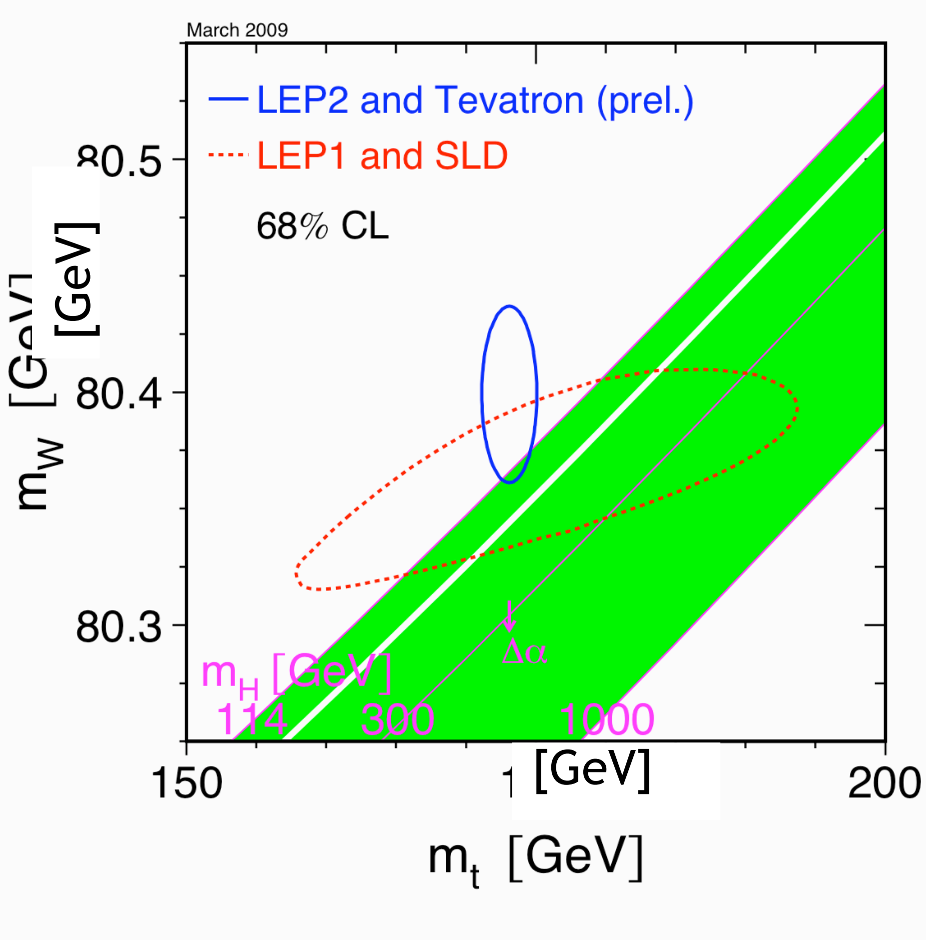


Tevatron/LHC expect to improve precision to ~1 GeV

Implications for the Higgs Boson

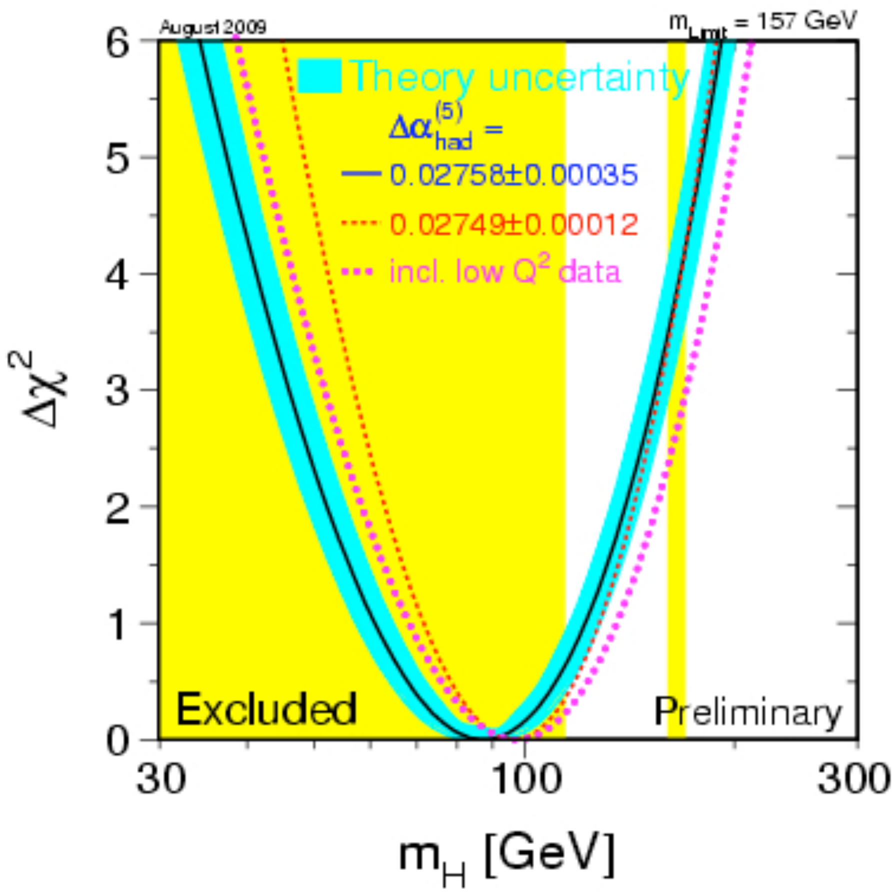
LEPEWWG 03/09

Relation: M_W vs m_{top} vs M_H



Standard Model still works!

$m_H = 87^{+35}_{-26}$ GeV



Indirect constraints:

m_H<163 GeV @95%CL

Backup Slides

Already happened in History!

[H. Murayama]

- Analogy in electromagnetism:
  - Free electron has Coulomb field: $\Delta E_{\rm Coulomb} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_e}.$
  - Mass receives corrections due to Coulomb field:
    - $(m_e c^2)_{obs} = (m_e c^2)_{bare} + \Delta E_{\rm Coulomb}.$
    - With $r_e < 10^{-17}$ cm: $0.000511 = (-3.141082 + 3.141593)\ \text{GeV}.$
  - Solution: the positron!

$$\Delta E = \Delta E_{\rm Coulomb} + \Delta E_{\rm pair} = \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e}\ .$$

Problem was not as bad as today's but solved by new particles: anti-matter

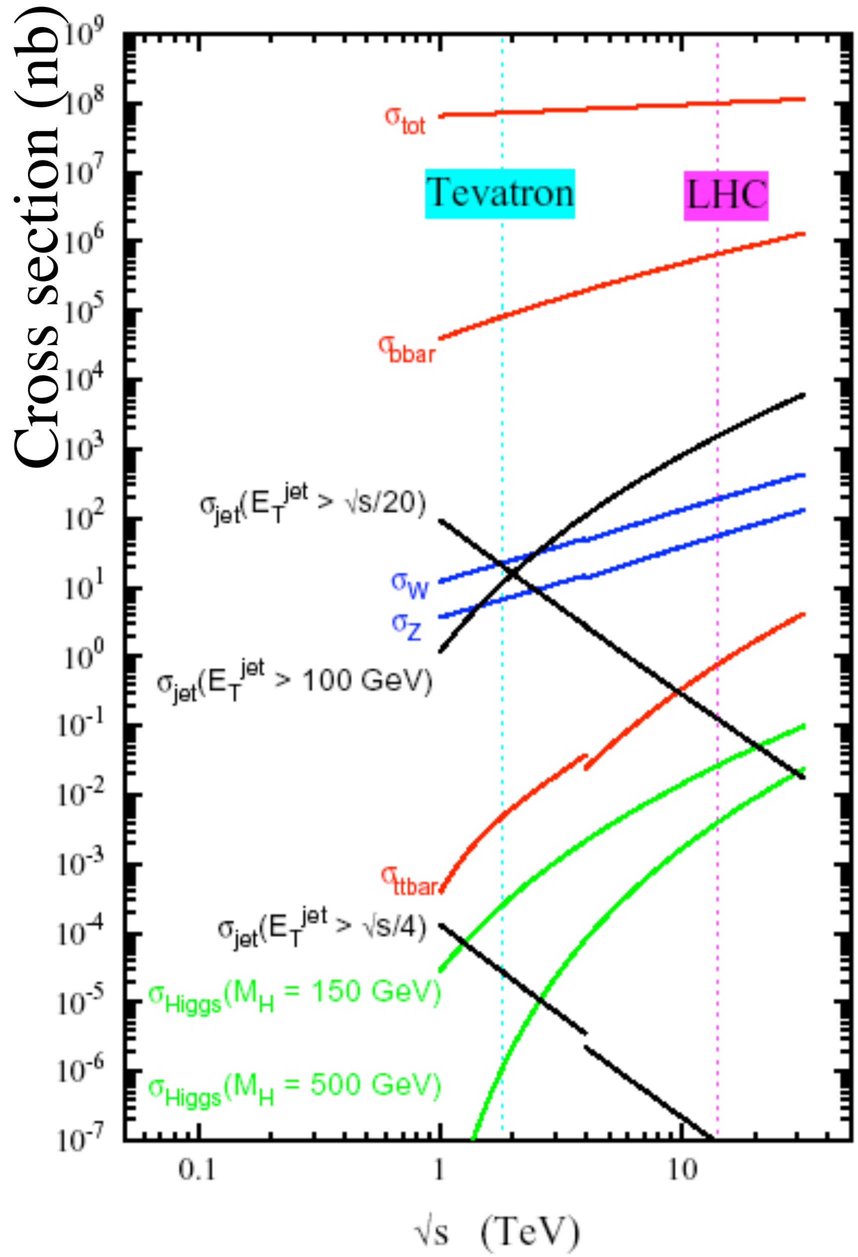
Paul Dirac's View of History

When I first thought of the idea I thought that this particle would have to have the same mass as the electron, because of the symmetry between positive and negative masses and energies which occurs all the way through this theory. But at that time the only elementary particles that were known were the electron and the proton. I didn't dare to postulate a new particle. The whole climate of opinion in those days was against postulating new particles, quite different from what it is now. So I published my work as a theory of electrons and protons, hoping that in some unexplained way the Coulomb interaction between the particles would lead to the big difference in mass between the electron and the proton.

Of course I was quite wrong there and the mathematicians soon pointed out that it was impossible to have such a dissymmetry between the positive and negative energy states. It was Weyl who first published a categorical statement that the new particle would have to have the same mass as the electron. The theory with equal masses was confirmed a little later by observation when the positron was discovered by Anderson.

Cross Sections at Tevatron and LHC

- A lot more "uninteresting" than "interesting" processes at design luminosity ($L=10^{34}\ cm^{-2}s^{-1}$)
  - Any event: 10^9 / second
  - W boson: 150 / second
  - Top quark: 8 / second
  - Higgs (150 GeV): 0.2 / second
- **Trigger** filters out interesting processes
  - Makes fast decision of whether to keep an event at all for analysis
  - Crucial at hadron colliders
- Dramatic increase of some cross sections from Tevatron to LHC
  - Improved discovery potential at LHC



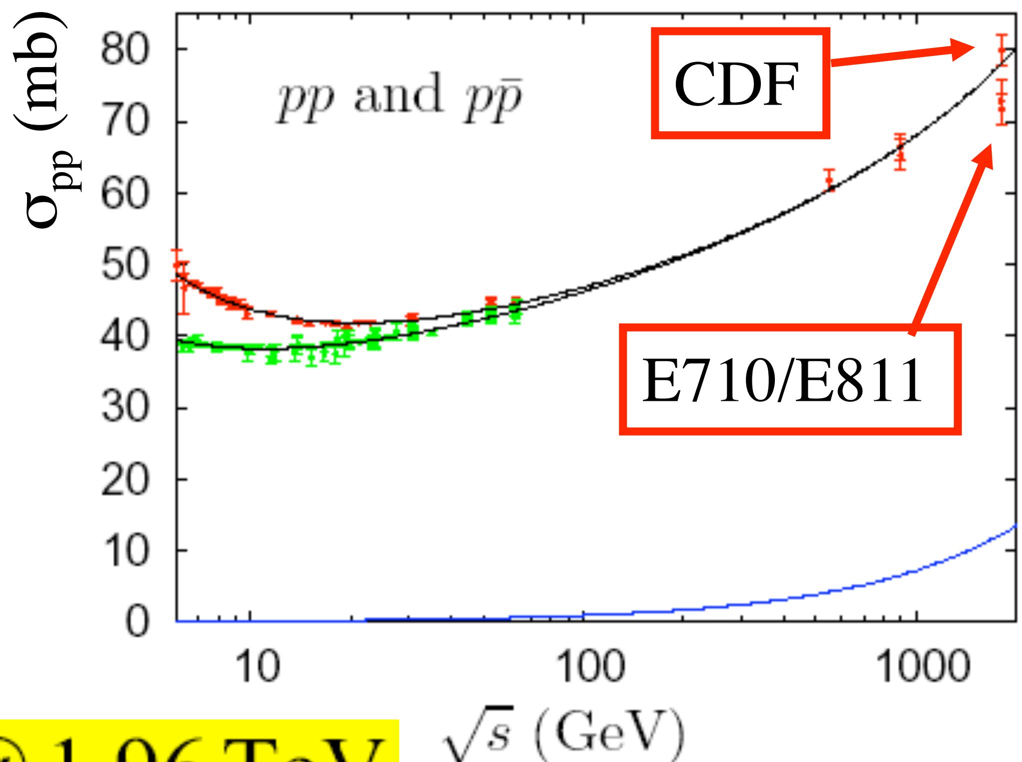
Luminosity Measurement

$$R_{pp} = \mu_{pp} \cdot f_{BC} = \underbrace{\sigma_{inel} \cdot \varepsilon_{pp}}_{\sigma_{LM}} \cdot \delta(L) \cdot L$$

L – luminosity
f_{bc} – Bunch Crossing rate
μ_a – # of pp / BC

σ_{inel} – inelastic x-section
ε_{pp} – acceptance for a single pp
$\delta(L)$ – detector non-linearity

- Measure events with 0 interactions
  - Related to R_{pp}
- Normalize to measured inelastic pp cross section



$$\overline{\sigma}_{in} = 60.7 \pm 2.4 mb \ @ \ 1.96\ \text{TeV}$$